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Effect of feed pitch on formability in tube expansion using ball spin forming

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Abstract. This study proposes a simple and localized forming method using a train of four balls in a tube-hoop direction that expands tube diameter at arbitrary axial positions. The balls travel in the tube direction while rotating around the tube axis. Compared with conventional methods, the expansion mechanism is compact as only one input-rotational drive forms taper and parallel sections. This paper particularly focuses on the effect of feed pitch for the parallel section forming and the ball gap to the cylinder on dimensional precision. An outer cylinder was used for securing the outer diameter as the inner surface of the cylinder can suppress the overshoot of the tube diameter. The experimental results verified the effect of the cylinder. When the ball gap to the cylinder was small enough to push the tube wall to the cylinder-inner surface, the tube diameter was stable at the target value regardless of the feed pitch for the parallel section forming. The tube thickness t decreased to 0.5 mm with increase of the clearance between the balls and the cylinder-inner surface just as designed. However, the thickness could not be less than 0.5 mm.

Introduction

Tubes are used in various fields, such as automotive parts, aircraft parts, heat exchangers, and construction materials, and there are various forming methods to manufacture according to their purpose[1]. In forming a tube, tube end forming is simple. The die can be pressed against the tube end to form the tube end[2]. In the case of tube nosing, a method has been proposed to increase productivity and forming limits by pressing a die with a rotating relief against the tube end[3]. In the case of tube expansion, a method of forming by inserting and moving the plug into the inside of the tube has been proposed[4]. Forming the center of the tube tends to complicate the structure of the machine due to the radial movement of the tool. In the case of diameter reduction forming, spinning has been used as an effective means [5]. Tube expanding in the centers of the tube is more difficult and the structure of the forming machine is more complex. Wines et al. proposed a forming method where the radial displacement of the ball train is realized by a tapered plug inserted inside the ball train [6]. According to this method, the machine is complex because the rotation of the tube, the movement of the taper plug, and the movement of the ball train are controlled independently of each other. This tube expansion processes require large forming equipment and cannot easily expand tubes at workplaces for plant engineering and others.

This study proposes a simple and localized forming method using a train of four balls in a tube-hoop direction that expands tube diameter as shown in Fig. 1. The balls travel in the tube direction while rotating around the tube axis. Compared with conventional methods, the expansion mechanism is compact as only one input-rotational drive forms taper and parallel sections. In a previous study, a prototype machine based on this proposal was built and experiments were conducted for investigating the effect of the feed pitch for the parallel section on the outer diameter and wall thickness. The previous study did not apply a cylinder or other tools as a diameter constraint, and then the outer diameter and thickness were unstable and changed in the tube-axial direction. The results showed that overshoot occurred at all feed pitches and that the amount of overshoot increased as the feed pitch increased. It was also found that the feed pitch did not affect the thickness.

This paper investigates the effect of feed pitch for the parallel section P_2 forming and the ball gap to the cylinder γ_α on the tube-outer diameter and thickness. An outer cylinder was used for suppressing the overshoot of the outer diameter and improving the diameter precision.

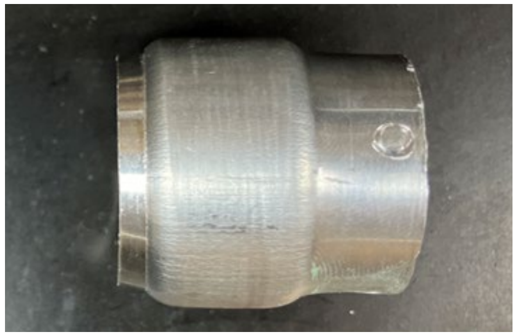


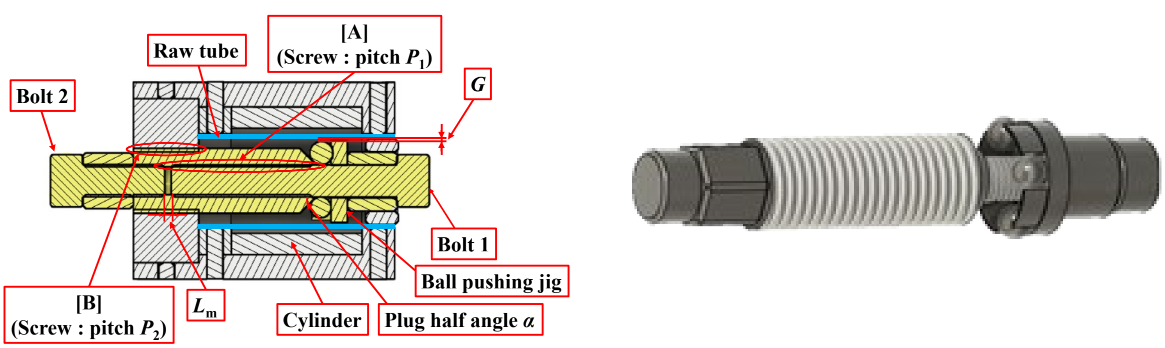
Fig. 1. Expanded tube.

Machine configuration and forming process

Fig. 2(a) shows a longitudinal section of the expansion machine and Fig. 2(b) shows a 3D model of the yellow part in Fig. 2(a). Note that parts [A] and [B] are screws. Fig. 3 shows a schematic diagrams of the forming process. The forming process can be divided into the first process for forming tapered section and the second process for forming expanded parallel section. A rotary drive is applied to Bolt 1 in the first and second steps. In the first step of taper forming, Bolt 1 moves forward while rotating along the sliding part [A] of the screw. The ball-pushing jig gives the balls a circumferential orbital motion so that the balls move forward along the plug slope with an increasing orbital radius. This results in taper forming (Fig. 3 (a)). The second step, forming the expanded parallel section, starts when Bolt 1 encounters Bolt 2, and the sliding part transitions from the screw [A] to [B]. The orbital radius of the balls is constant, so parallel sections are formed (Fig. 3 (b)). In this way, the tapered and parallel sections are formed simply by applying a rotary drive to Bolt 1. The amount of expansion γ is expressed by the following Eq. 1.

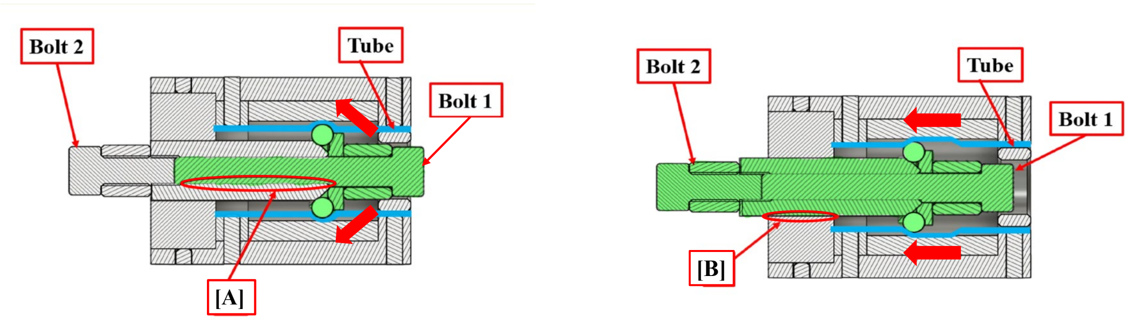
$$\gamma = 2L_{\mathrm{m}}\tan\alpha - 2G \quad (1)$$

Where L_{m}: clearance between Bolt 1 and Bolt 2, α: the plug half angle, and G: clearance between the tube and the balls at the initial position. The feed pitches P_1 for 1st step and P_2 for 2nd step of ball per revolution are determined by the screw pitches of Bolt 1 and Bolt 2.



(a)Longitudinal section of expansion machine (b) 3D model

Fig. 2. Schematic diagrams of the expansion machine.



(a) 1st step (b) 2nd step

Fig. 3. Schematic diagrams of forming (Green part: moving tools).

Experimental condition

Table 1 shows the conditions of this experiment. The experiment investigated the effect of feed pitch for the parallel section P_2 on dimensional precision. The effect of the ball gap to the cylinder γ_α on the outer diameter D and thickness t was also studied. The ball gap to cylinder γ_α is defined as shown in Fig. 4. If the gap γ_α is smaller than thickness t, the tube wall is ironed by the balls.

Table 1. The condition of this experiment.

Plug half angle α [°]	45
Feed pitch P_1 [mm·rev^{-1}]	1.5
Feed pitch P_2 [mm·rev^{-1}]	1.25, 1.0, 0.75, 0.5
Ball gap to cylinder γ_α [mm]	1.0, 0.75, 0.5, 0.25
Ball diameter [mm]	7.5
Cylinder inner diameter [mm]	32.03
Material of raw tube	A1070-H14
Length of raw tube l_0 [mm]	30
Outer diameter of raw tube D_0 [mm]	28
Thickness of raw tube t_0 [mm]	1.0

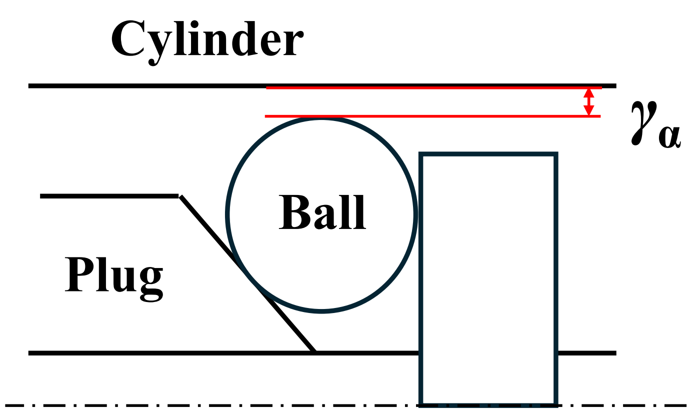


Fig. 4. Schematic illustration of ball gap to cylinder γ_α.

Evaluation of dimensional precision of expanded tube

The axial distribution of the outer diameter *D* and thickness *t* of the expanded tube was measured. As shown in Fig. 5, eight lines were scribed at 45° pitch in the circumferential direction, and four lines were scribed at 2 mm pitch in the longitudinal direction from the starting point of the parallel section of the expanded tube, and the outer diameter *D* was measured using a digital caliper and the wall thickness *t* using a micrometer at the intersection points. The data obtained were averaged in the circumferential direction to obtain the axial distribution of outer diameter *D* and wall thickness *t*.

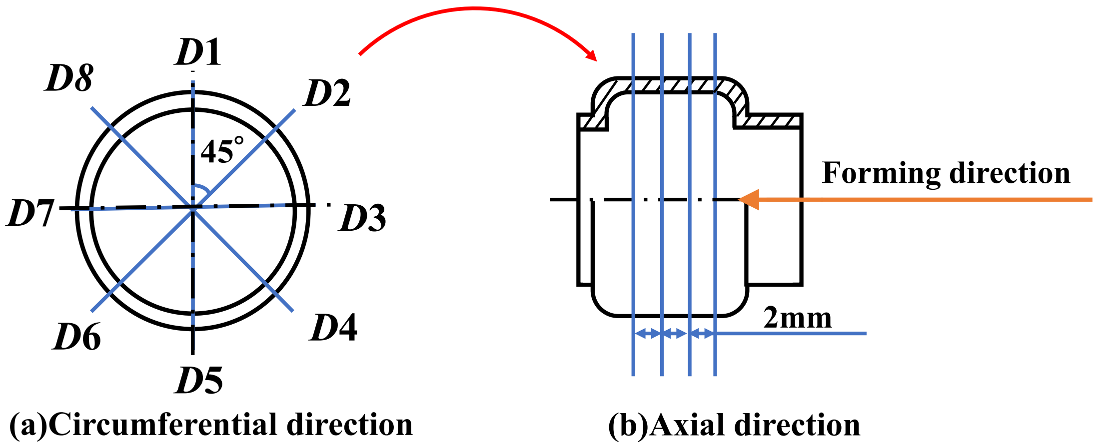
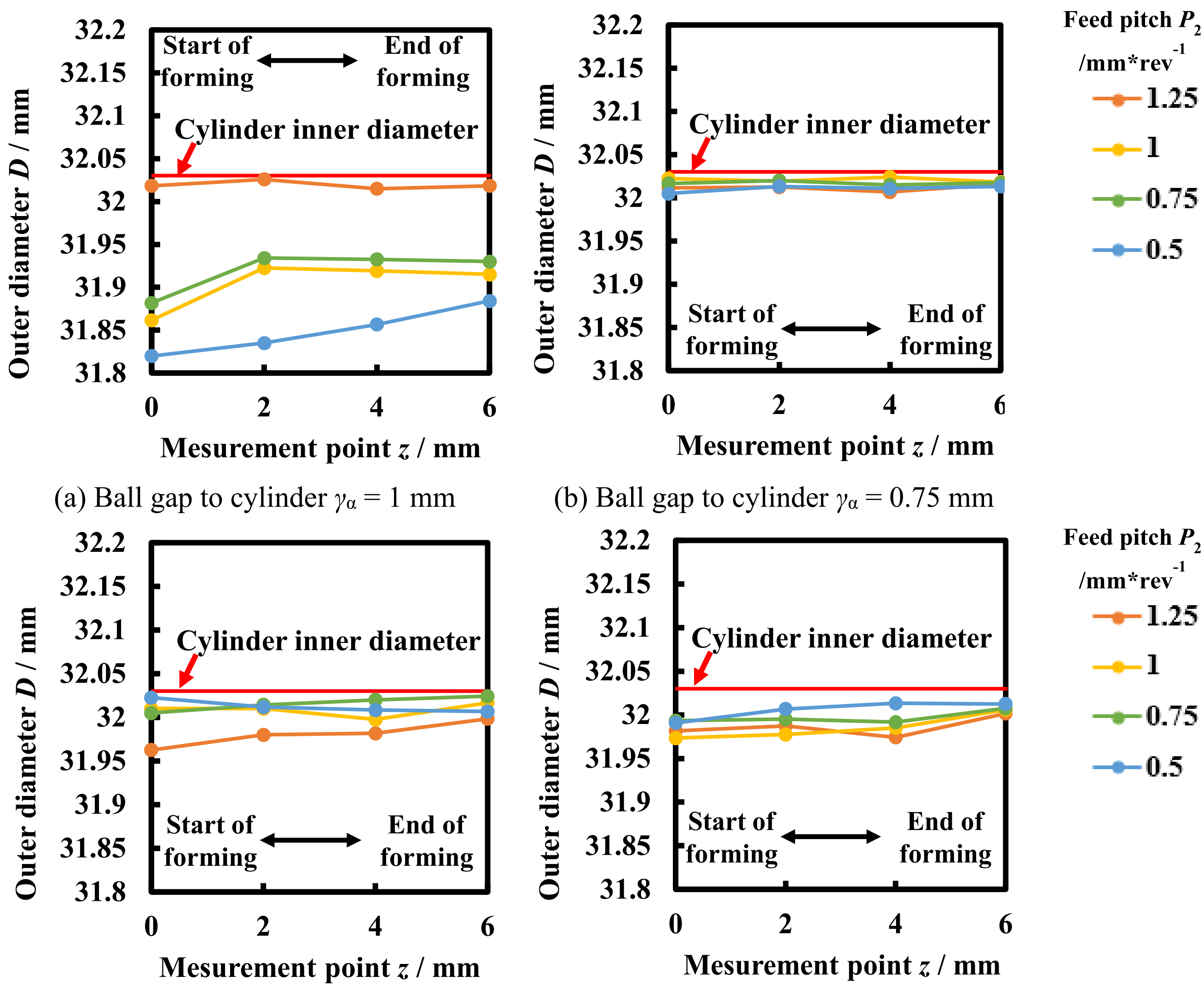


Fig. 5. Position for evaluating thickness t and outer diameter D.

Results and discussion

(1) Outer diameter. Fig. 6(a) shows the effect of feed pitch for the parallel section forming P_2 on outer diameter *D* when the ball gap to the cylinder γ_α = 1 mm. If overshoot does not occur, the tube-outer surface does not contact the cylinder-inner surface as the gap γ_α is equal to the initial tube thickness t_0 and the thickness after expansion *t* must be smaller than t_0. When P_2 = 1.0 - 0.5 mm·rev^{-1}, *D* and increased as P_2 increased. This would be attributed to the overshoot which must increase with increase of P_2. It is noteworthy that the diameter *D* is equal to the cylinder-inner diameter when P_2 is 1.25 mm·rev^{-1}, and this would be attributed to a large overshoot.

Figs. 6(b), (c), and (d) show the effect of P_2 on *D* for γ_α = 0.75 mm, 0.5 mm, and 0.25 mm. Under all three conditions, the error of *D* to the cylinder-inner diameter was within 0.1 mm. This is because the ball gap to the cylinder γ_α was smaller than the naturally-expanded thickness t_n which was an assumed thickness after expansion without the constraints by the cylinder. Therefore, the tube wall must have been ironed between the ball and the cylinder-inner surface. It should be noted that the diameter error to the cylinder diameter increased with decrease of the gap γ_α. This would be due to excessive ironing which might cause unstable deformation.



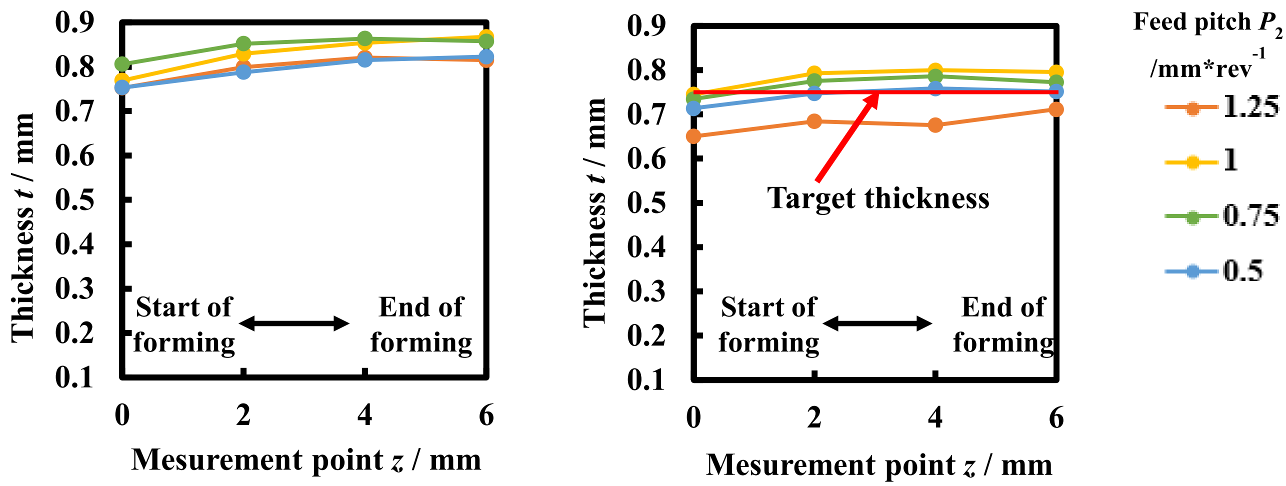
(a) Ball gap to cylinder $\gamma_\alpha = 1$ mm (b) Ball gap to cylinder $\gamma_\alpha = 0.75$ mm

(c) Ball gap to cylinder $\gamma_\alpha = 0.5$ mm (d) Ball gap to cylinder $\gamma_\alpha = 0.25$ mm

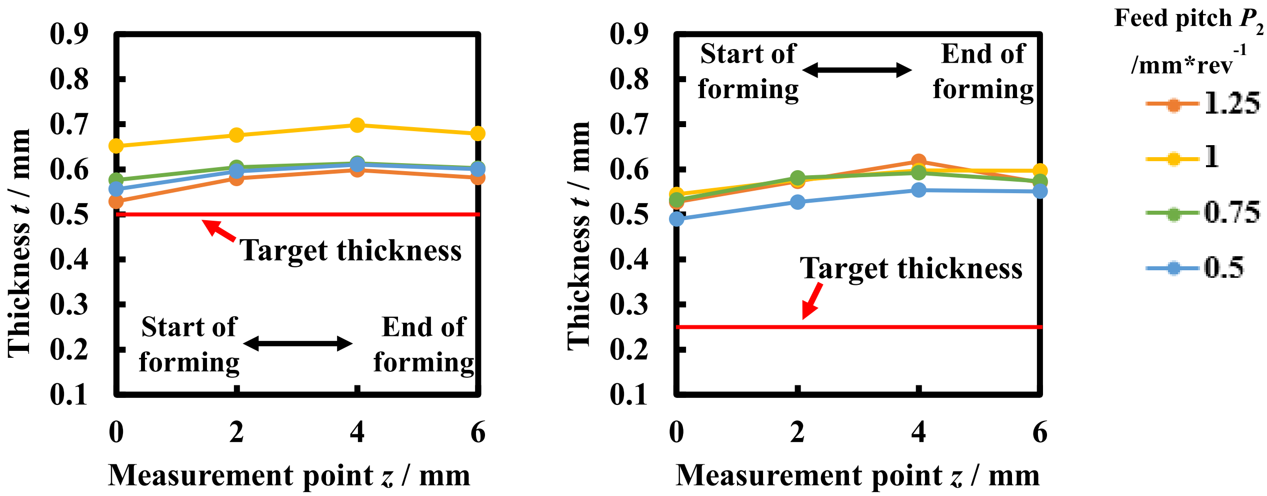
Fig. 6. Effect of feed pitch P_2 on outer diameter D.

(2) Thickness. Fig. 7(a) shows the effect of the feed pitch P_2 on the wall thickness t at the ball gap to the cylinder $\gamma_\alpha = 1$ mm. The thickness t was around 0.8 mm regardless of P_2. This is because the gap γ_α was more than the naturally-formed thickness t_n without the cylinder and the thickness was not ironed by the ball.

Figs. 7(b), (c), and (d) show the effect of P_2 on t for $\gamma_\alpha = 0.75$ mm, 0.5 mm, and 0.25 mm, respectively. The target thickness was the ball gap to the cylinder γ_α as the gap γ_α was small enough to iron the tube wall with the balls. The thickness t was close to the target thickness when $\gamma_\alpha = 0.75$ mm, while t was larger than the target thickness when $\gamma_\alpha = 0.5$ and 0.25 mm. This is thought to be due to unstable deformation of the tube wall and elastic deformation of the supporting tools as the ironing deformation was very severe. No clear effect of P_2 on t was observed.



(a) Ball gap to cylinder γ_α = 1 mm (b) Ball gap to cylinder γ_α = 0.75 mm



(c) Ball gap to cylinder γ_α = 0.5 mm (d) Ball gap to cylinder γ_α = 0.25 mm

Fig. 7. Effect of feed pitch P_2 on thickness t.

Conclusion

This paper proposed a simple and localized forming method using a train of four balls in a tube-hoop direction that expands tube diameter at arbitrary axial positions. A prototype tool-set was built up based on the proposed method and experiments were conducted to verify the effectiveness of the proposed method and check the dimensional precision of the formed parts by changing the feed pitch P_2 and ball gap to cylinder γ_α for forming of the expanded parallel section with a cylinder placed on the outer surface of the tube. The following conclusions were obtained.

1) The proposed method successfully expanded the tube diameter in the middle of the longitudinal direction with a concise mechanism using only one input drive. The expansion process is composed of step 1 of taper forming and step 2 of parallel forming.
2) Setting an outer cylinder was effective for securing the outer diameter of the parallel section.
3) The cylinder-inner diameter should be the target diameter, while the ball gap to the cylinder should be the target thickness.
4) The dimensional precision changes depending on the ball gap to cylinder γ_α, and the most appropriate value was clarified for the gap γ_α.
5) When the gap γ_α is equal to the initial tube thickness t_0, the feed pitch P_2 affects the expanded diameter D. When the feed pitch P_2 was large enough, the overshoot was large enough,

expanding the tube diameter to the cylinder-inner diameter. However, the tube thickness t is smaller than the gap γ_α.

6) When the gap γ_α was 0.75 mm for the tube thickness t_0 = 1.0 mm, the tube must have been ironed between the balls and the cylinder-inner surface appropriately, and the dimensional precision was highest, i.e. diameter D was almost the same as the cylinder-inner diameter and thickness t was almost the same as the gap γ_α.

7) When the gap γ_α was smaller than 0.75 mm, the tube must have been ironed severely, resulting in a smaller diameter than the cylinder-inner diameter and a thicker wall than the gap.

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