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EXAMINATION OF WORKING CONDITION FOR REDUCING THICKNESS VARIATION IN TUBE DRAWING WITH PLUG

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Abstract. The present research carried out a series of analyses using the finite element method (FEM). The analyses investigated the effect of working condition on thickness variation after drawing a tube with initial thickness distribution. As a result, it was notably revealed that application of dies with small half angle below 5 degrees was prominently effective for levelling the thickness variation. This effect was strengthen by employing tubes with thicker walls and larger diameters. Moreover, the mechanism of levelling the thickness variation was also examined. The small die angle affects the contact length at die approach, and the contact length at thinnest side becomes longer than that at the thickest side. The difference of the contact lengths equalizes the thicknesses of the thinnest and thickest sides. The analyses also predicted the thickness variation should almost be zero under an optimum condition.

1 INTRODUCTION

Drawing is a common and general process, which is placed in one of the last stages for manufacturing elongated products of bars, wires and tubes. Drawing process determines many characteristics of the products, including mechanical properties, hardness, residual stresses, surface integrities, straightness and so on. Although straightener, which is placed after drawing, improves straightness and alleviates residual stresses, these properties should previously be improved in the drawing process for stable manufacturing.

There are many research works for drawing, assuming that drawing should be conducted in an axisymmetric manner. Some drawing methods were proposed for levelling residual stresses in bar drawing. Application of light reduction in area at the final drawing stage is very effective for levelling residual stresses [1]. This light reduction drawing is effective for copper, aluminum, high carbon steel as well as medium carbon steel [2]. Shape optimization of die was conducted and it was revealed that double-tapered die with light angle at the second taper was also effective for levelling residual stresses [3]. It was also pointed out that high reduction in thickness is effective for levelling residual stresses in tube drawing using plug [4].

There are some research works on asymmetric phenomena in bar or tube drawing. One of the concerns is straightness. It was found that there are two ranges of reduction in area which effectively improve straightness in bar drawing [5]. Another concern is thickness variation in the case of tube drawing. The thickness variation derives from the tube fabrication processes.

Tubes and pipes are fabricated by either (1) electric resistance welding process (ERW process) or (2) seamless tube fabrication. The ERW process used a sheet metal which is rolled in advance, and the rolling process inevitably yields thickness variation. The seamless tube fabrication process is composed of piercing, mandrel-mill rolling and reducing-mill rolling, and these processes also yield thickness variation [6]. It has been desired that the drawing process should eliminate or reduce the thickness variation, which is yield by the tube fabrication processes. Foadian et al. proposed a unique drawing method using tilting die according to the thickness variation [7]. However, the amount and the direction of thickness variation in hoop direction should be known in advance for the arrangement of the die orientation.

The present research conducts a series of analyses using the finite element method (FEM) for the investigation of the effect of working condition on thickness variation after drawing tubes with a plug. In particular, this research focuses upon the effect of die angle, and tries to find the optimum condition. Furthermore, the mechanism of thickness change during drawing and the effects of the thickness reduction are also examined.

2 ANALITICAL CONDITION FOR TUBE DRAWING WITH PLUG

2.1 Drawing condition and FEM model

A schematic illustration of drawing a tube with a plug is shown in Fig. 1 and the drawing condition is shown in Table 1. The die has an approach of straight tapered shape. The thickness variation is assumed to exist in the initial tube. The plug is a straight cylinder, which is supported by an elongated rod. The plug should freely and flexibly move in the orthogonal direction to the rod axial direction due to elastic deformation as it is actually longer than or equal to 10,000 mm in the industry.

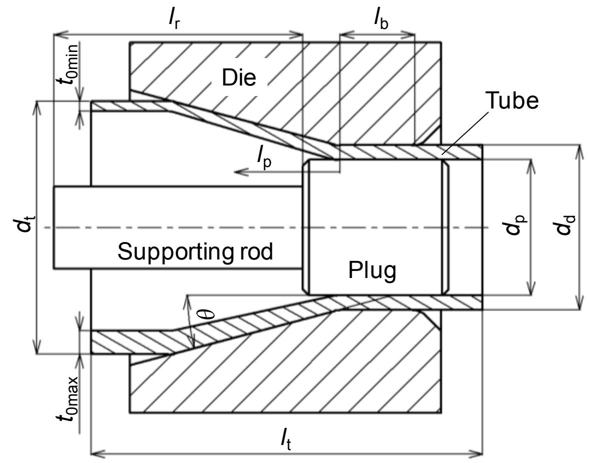


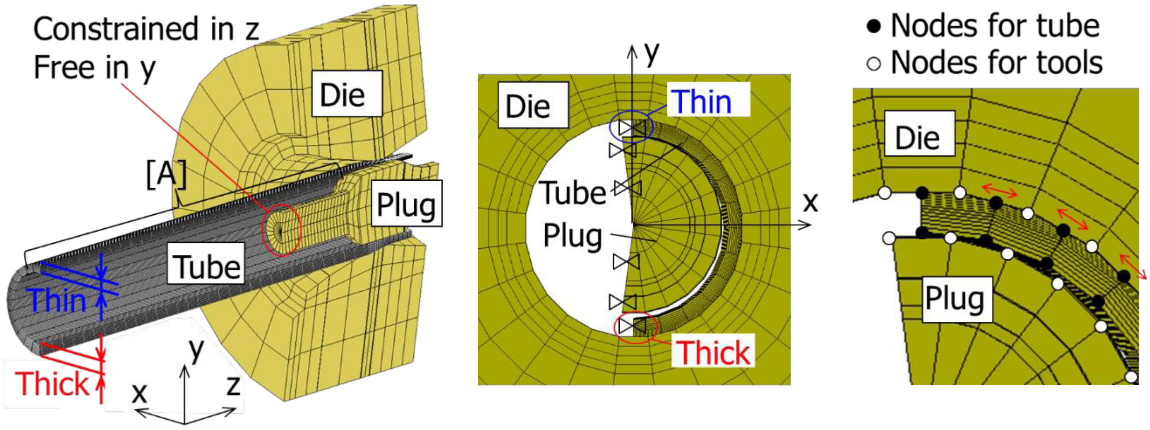
Figure 1: Drawing a tube with a plug

Table 1: Drawing condition

Die	Type		Rigid
	Die hole diameter d_d /mm		30
	Die half angle θ/°		4.5 - 10
	Bearing length l_b /mm		4
Plug	Type		Elastic
	Plug diameter d_p /mm		24.4
	Average clearance bw die & plug C_L $C_L = (d_d\text{-}d_p)/2$ /mm		2.8
Tube	Type		Plastic
	Material of tube		A1070
	Tube outer diameter d_t /mm		31.5
	Tube thickness on average t_{0ave} /mm Thickness reduction R_{dt} (%) $R_{dt} = (t_{0ave} - C_L)/ C_L$		2.9 - 3.2 3.5 -14.3
	Length of tube l_t /mm		170
	Initial thickness variation $\Delta t_0 = t_{0max}\text{-}t_{0min}$ /mm		0.2
	Division in FEM	Axial	0.5 mm/div
		Radial	7div. (progressive)
		Hoop	15 deg./div
Friction coefficient			0.07

The FEM model is shown in Fig. 2. A half model is employed due to the symmetricity on the y-z plane. All nodes on the y-z plane are constrained in the x direction. The upper side of the tube cross section is thin and the lower side is thick, and the shape of the cross section is constant in the tube axial direction for the straight part of the tube which is denoted by [A] in Fig. 2(a). The supporting rod is much shorter than the actual one in the manufacturing line in the industry. The end face of the rod is constrained in the z direction, but free in y direction as shown in Fig. 2(a). Therefore, the plug freely moves in the y direction just as in the manufacturing line. The nodes of the tube are located between the nodes on the tools in the hoop direction so that the nodes should freely move in the hoop direction as shown in Fig. 2(c).

The finite element analyses were conducted using the commercial code ELFEN, which was developed by Rockfield Software Limited, Swansea. An 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 hexahedral 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 8-node hexahedral elements [8].



(a) Bird-eye view (b) Rear view (c) Magnified rear view

Figure 2: FEM model for drawing

2.2 Evaluation method of dawn tube

The thickness variation ratio E_c was defined by the following equation, and the comparison was made between the values before and after drawing:

$$E_c = \frac{\Delta t}{t_{ave}} = \frac{t_{max} - t_{min}}{(t_{max} + t_{min})/2} \tag{1}$$

where t_{max} is the maximum tube thickness and t_{min} is the thinnest one.

The change of thickness must be affected by stresses during drawing. Average stresses in the thickness direction was used for examination of the mechanism as the thickness change should appear as a result of the total deformation in the thickness direction. The average stresses σ are calculated by the following equation:

$$\sigma = \sum_{i=1}^{N_{dr}} \left(\frac{(y_{i+1} - y_i) \times (\sigma_{i+1} + \sigma_i)/2}{(y_{i+1} - y_i)} \right) \tag{2}$$

where i is the node number, N_{dr} is the number of elements y direction, y_i is the node position in y direction and σ_i is the stress at node i. The nodes for calculation of average stress is shown in Fig. 3.

The thickness variation ratio and the average stress are calculated during and after drawing. Figure 4 shows the definition of the position l_a after drawing and l_p during drawing where the thickness variation or the average stress were evaluated. The vertical position of plug, which would dominates the thickness variation was evaluated according to the drawing stroke l_d.

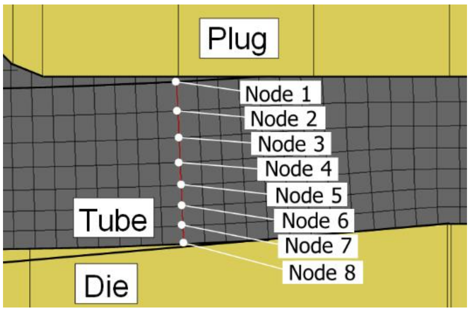
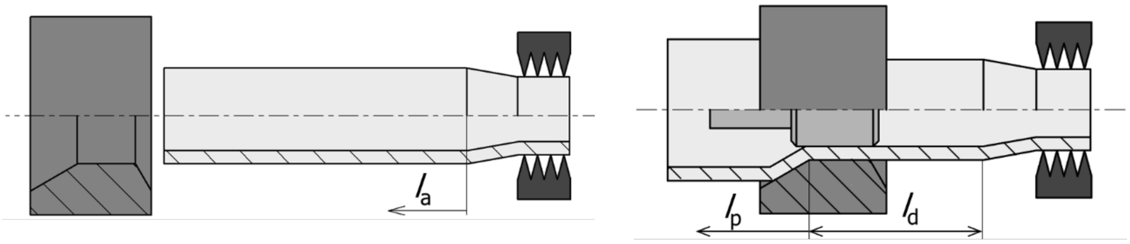


Figure 3: Nodes for calculation of average stress in the thickness direction



(a) After drawing (b) During drawing

Figure 4: Definition of positions for evaluating thickness variation and average stress in thickness

3 RESULTS OF THE FINITE ELEMENT ANALYSIS

3.1 Effect of die angle and thickness reduction on thickness variation

Figure 5 shows the effect of die half angle on thickness variation after drawing. The thickness variation E_c changes from the head to the tail of the tube. The change of the thickness variation should be attributed to gradual position change of plug in vertical direction (y) during drawing. If a longer tube is used, the position of plug will become stable at the tail side, resulting in a stable thickness variation. The effect of die angle is prominent at the tail side, and the thickness variation E_c was effectively levelled when the die half angle θ was lower than or equal to 5 degrees.

Figure 6 shows the effect of initial average thickness on the thickness variation E_c after drawing for the low die half angle of 5 degrees. The effect of initial average thickness t_{0ave} is prominent at the tail side, and the thickness variation E_c effectively decreased with the increase of initial average thickness t_{0ave}. When the initial average thickness is larger than or equal to 3.1mm, in other words, when average thickness reduction R_{dt}, which was defined inside Table 1, is larger or equal to about 10 %, the thickness variation was effectively levelled.

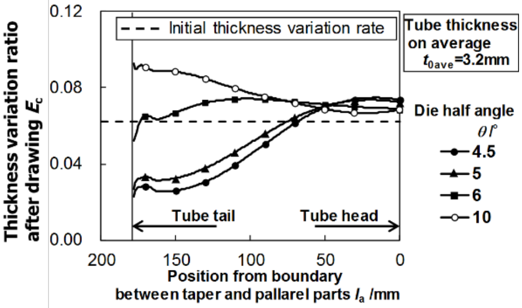


Figure 5: Effect of die angle on thickness variation after drawing

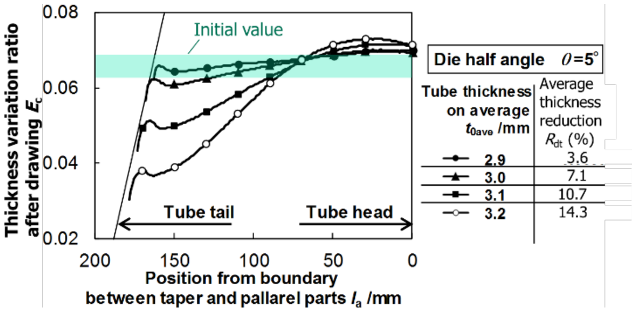


Figure 6: Effect of average thickness on thickness variation after drawing

3.2 Mechanism on decrease of thickness variation by applying the low die angle

Figures 7 shows the mechanism of levelling thickness variation when the die half angle was low and the thickness reduction was large. There are three regions, (a), (b) and (c), which feature the change of thickness variation as follows:

- Region (a): Gradual decrease of thickness variation.

The inner surface does not contact with the plug surface. Compressive force must appear in the hoop direction of tube, and the hoop compressive stress should be higher at the thin side than that at the thick side. As a result, the thickness should increase more at the thin side than at the thick side, resulting in gradual decrease of thickness variation.

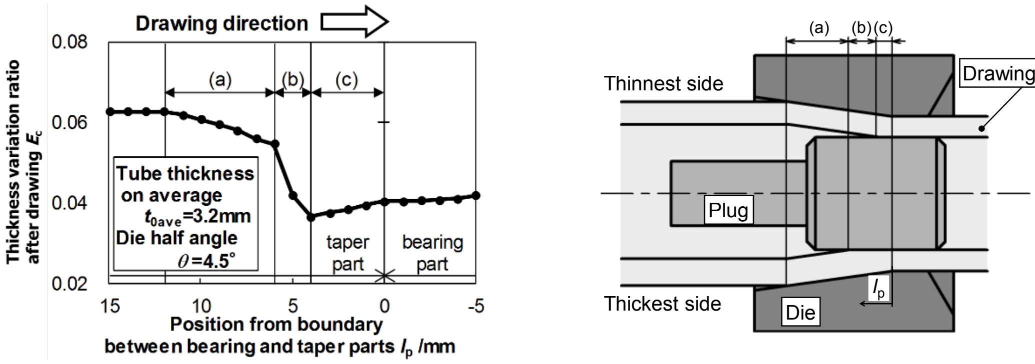


Figure 7: Thickness variation change during drawing
(die half angle θ=4.5°, initial average thickness t_{0ave}=3.2mm)

- Region (b): Rapid decrease of thickness variation.

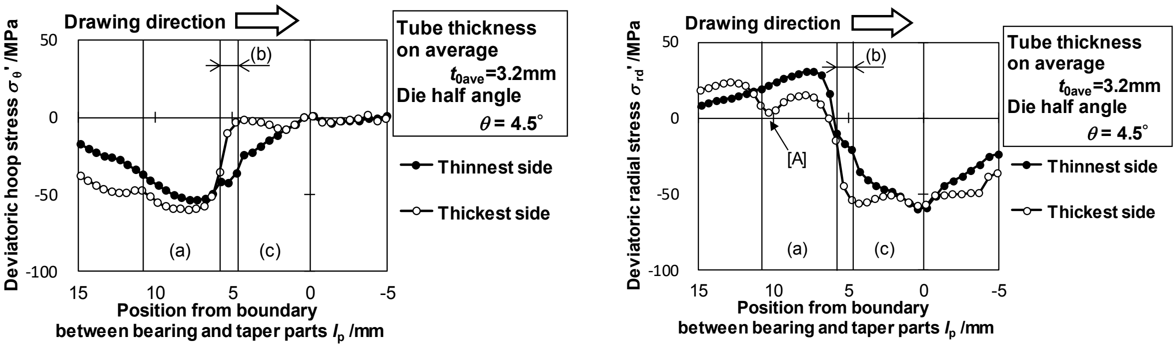
The thicker side of the inner surface contacts with the plug surface, but the thinner side does not. The thickness on the thicker side decreases as the tube wall is constrained between the plug and the die. On the other side, the thickness of the thinner side does not change much. As a result, the thickness variation rapidly decreases.

- Region (c): Slight increase of variation ratio.

The thicker and thin sides of the inner surface contacts with the plug surface. The tube wall at both of the thicker and thinner sides is constrained by the die and the plug. Therefore, the absolute value of the thickness variation, t_{max}-t_{min} does not change, while the thickness itself decreases at this region with decrease of the die diameter along z axis. As a result, the thickness variation ratio E_c slightly increases.

Figure 8(a) shows deviatoric hoop stress which dominates plastic deformations in hoop direction. Deviatoric hoop stresses of the thickest and thinnest sides are compressive at the region (a), and that means the tube shrinks in the hoop direction. However, that of the thickest side changes to almost zero at the region (b), where the thickest side is constrained by the die and the plug. That means the thinnest side continues to shrink while the thickest stops to deform in the hoop direction at the region (b).

Figure 8(b) shows deviatoric radial stress which dominates plastic deformation in thickness direction. Deviatoric radial stress of the thinnest side is larger than that of the thickest side at the region (a) with the drop of the value at the thickest side at [A]. That means thickness of the thinnest side increases more than that of the thickest side, resulting in the decrease of the thickness variation. The negative value of deviatoric radial stress of the thinnest side is smaller than that of the thickest side at the region (b), and that means thickness of the thickest side decreases more than that of the thinnest side, resulting in the decrease of the thickness variation. Therefore, both of the regions (a) and (b) have the effect of levelling thickness variation.



(a) In hoop direction (b) In radial direction

Figure 8: Distribution of deviatoric stresses
(die half angle θ=4.5°, initial average thickness $t_{0\mathrm{ave}}$=3.2mm)

3.3 Effect of die angle on the mechanism of levelling thickness variation

Figure 9 shows the effect of the die half angle on the distribution of thickness variation during drawing. The final thickness variation at the exit of the region (c) decreased with the decrease of the die half angle θ. The effect of the die angle is attributed to the length of the regions (a) and (b), which have the effect of levelling thickness variation as explained in Figs. 7 and 8. The dies with low die half angles of 4.5 and 5 degrees have much longer regions of (a) and (b). Therefore, when the die half angle is less than or equal to 5 degrees, the thickness variation is effectively suppressed.

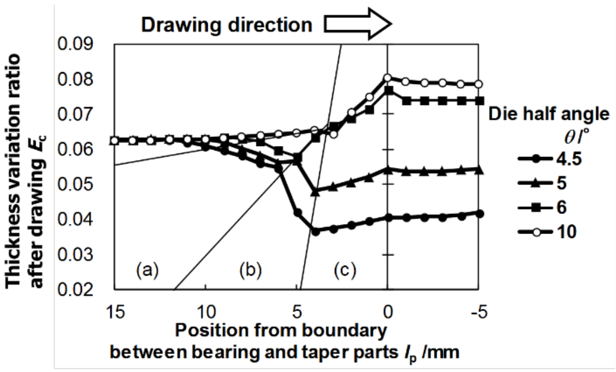


Figure 9: Effect of die angle on distribution of thickness variation during drawing (initial average thickness t_{0ave}=3.2mm)

3.4 Effect of initial average thickness on the mechanism of levelling thickness variation

Figure 10 shows the effect of the initial average thickness on the distribution of thickness variation. The final thickness variation at the exit of the region (c) decreased with the increase of the initial average thickness t_{0ave}. Even though the lengths of the regions (a) and (b) are not affected by t_{0ave}, thickness variation ratio E_c decreased for large t_{0ave}.

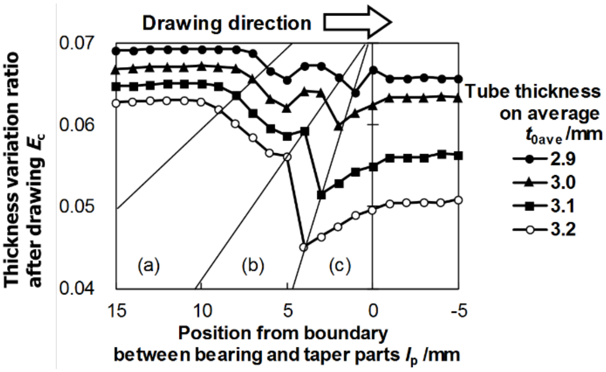


Figure 10: Effect of initial thickness on distribution of thickness variation during drawing (die half angle θ = 5 degrees, plug free in y)

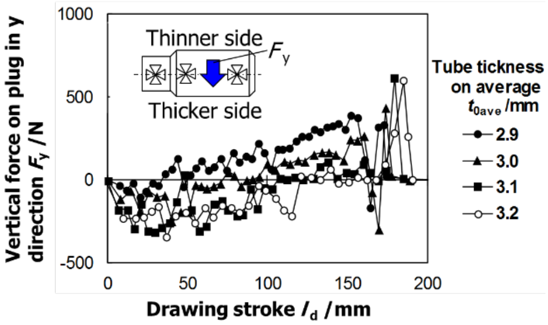


Figure 11: Effect of initial thickness on vertical force on plug (θ = 5 degrees, plug fixed in y for constant thickness variation)

Figure 11 shows the effect of the initial average thickness $t_{0\mathrm{ave}}$ on the vertical force F_y on plug in vertical direction (y). In this analysis, the plug was fixed in the vertical direction and the plug position in y direction δ_y was determined so that the thickness variation ratio E_c should be constant before and after drawing. The force F_y was defined as positive for the downward direction, and then the larger F_y of positive value means less thickness variation E_c should be realized when the plug is free in vertical direction (y). It is noteworthy that the vertical force F_y increased with increase of $t_{0\mathrm{ave}}$, and that means larger $t_{0\mathrm{ave}}$ should lead to less thickness variation E_c when the plug is free in y.

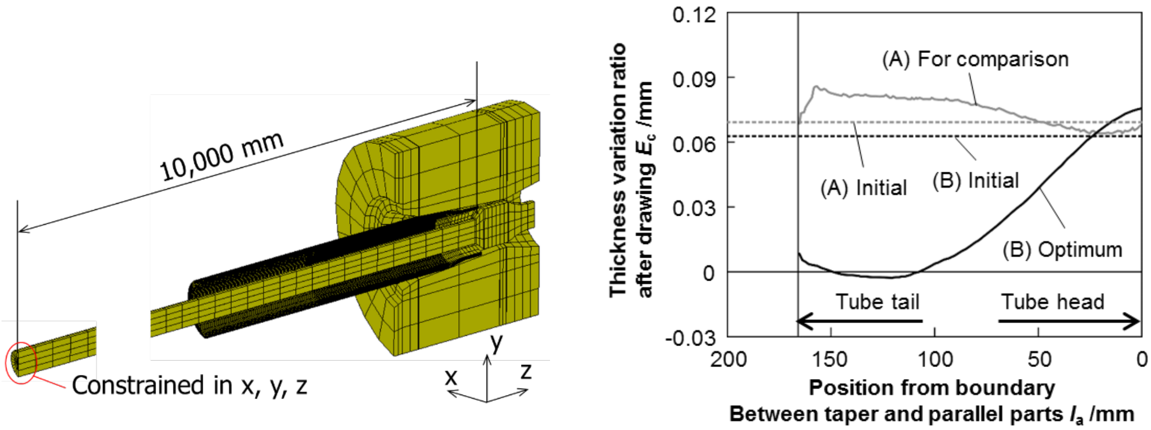
4 OPTIMUM CONDITION

The previous sections revealed that the optimum conditions should be low half die angle θ less than or equal to 5 degrees and large thickness reduction R_dt larger than or equal to 10 %. It would be also predicted that larger initial tube diameter would be desirable because it would enlarge the region (a), which has the effect of levelling thickness variation.

FEM analyses was conducted for the verification under the condition in Table 2 for comparison between the optimum condition (B) and another condition (A). The FEM results are shown in Fig. 12 with a long and elastic plug, the end of which is constrained in 3 directions. The optimum condition certainly levelled the thickness variation to zero at the latter end of the tube.

Table 2: Optimum condition and its comparison

Drawing condition		(A) For comparison	(B) Optimum
Die	Die half angle θ /°	10	5
Tube	Tube outer diameter d_t /mm	31.5	33
	Average tube thickness $t_{0\mathrm{ave}}$ /mm Average thickness reduction R_dt (%) (Initial thickness variation rate E_0)	2.9 3.6 (0.0690)	3.2 14.3 (0.0625)



(a) Model with long and elastic plug (b) Thickness variation

Figure 12: Thickness variation for optimum condition and for a compared condition

5 CONCLUSIONS

- The present research carried out a series of analyses using the finite element method (FEM) for the investigation of the effect of working condition on thickness distribution after drawing tubes.
- It was notably revealed that application of dies with low half die angle smaller than or equal to 5 degrees was prominently effective for levelling the thickness variation.
- This effect was strengthen by employing tubes with thicker walls with thickness reduction larger than or equal to 10 %.
- It was also suggested that the effect was also strengthen by employing tube with large diameter.
- Moreover, the mechanism of levelling the thickness variation was also examined.
- The FEM also predicted the thickness variation should almost be levelled to zero under the optimum condition.

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