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EFFECT OF INITIAL THICKNESS DEVIATION AND REDUCTION ON LONGITUDINAL AND CROSS-SECTIONAL PRECISION AFTER TUBE DRAWING USING PLUG

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Abstract. In this research, 2D and 3D FEM models are composed for the clarification of the effect of initial thickness distribution on its distribution after drawing and the residual stresses. In the 2D FEM, the minimum bare element number was determined in terms on both residual stress precision and calculation time. Based on the results of 2D FEM, the element number in 3D FEM was determined. Using the obtained 3D FEM, the effect of initial thickness distribution was clarified with the combination of thickness reduction. It was revealed that light reduction in thickness in plug drawing sometimes lead to increase of thickness deviation, against intuitive prediction based on tube drawing without plug. On the other hand, increase of thickness reduction resulted in decrease of thickness deviation. The mechanism of thickness change was also examined.

1 INTRODUCTION

Drawing is one of metal forming processes for manufacturing tubes, wires and bars, due to some advantages, which include high accuracy, high surface integrity, and improvement of mechanical properties by work hardening. Although drawing is a concise and simple process, there are still many problems to be solved, and then many research works have been conducted [1 - 3]. Most of the previous studies were conducted assuming the raw materials were axisymmetric. However, in the case of tube drawing, the initial tubes are asymmetric due to thickness variation which is inevitably generated in previous processes [4, 5].

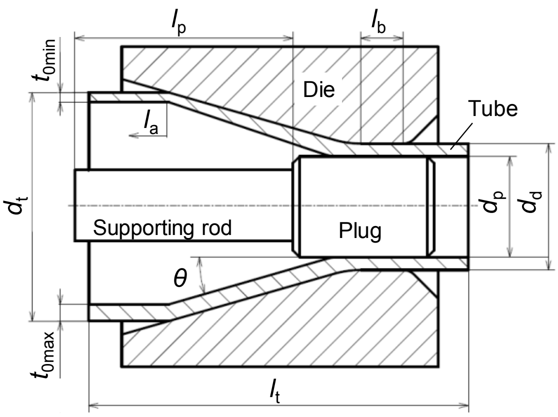
Quantitative understanding of thickness behaviour in tube drawing is important as drawing is positioned in the vicinity of the last stage of process line. If high precision is required for the tube thickness, machining should be applied after tube drawing. The less the thickness variation, the more efficiently material loss and machining time would be suppressed by reducing the depth of cut in machining. If required precision is not so high, machining may be omitted depending on the thickness variation. Therefore, prediction of thickness variation of drawn tube is important for deciding whether to apply machining and determining the depth of cut when machining is applied.

Experimental study is not sufficient for clarification of thickness behaviour in tube drawing. As experiment includes several disturbances at the same time, such as heterogeneous property of material surface and eccentricity between die axis and drawing axis, it is difficult to clarify the effect of thickness variation only [6]. In particular, when a plug is used for precise drawing and smoothness of inside surface, existence of plug would make the phenomena more complicated. Numerical studies, such as the finite element method (FEM) would be efficient for clarifying the effect of each disturbance and working condition.

In the present research, FEM model for tube drawing with plug was composed for examination of the effect of initial thickness variation and thickness reduction on cross-sectional and longitudinal precisions. The research also shows the mechanism on thickness behaviour with focus upon contact pressure on plug surface and plug position during tube drawing.

2 DRAWING SETUP

The commercial code ELFEN [7], which was developed by Rockfield Software Limited, Swansea, was used for the analysis of tube drawing with plug. Figure 1 shows the schematic illustration of tube drawing, and Table 1 shows drawing condition. 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 in 2D and hexagonal element in 3D were used because of the simplicity of the material deformation. The F-bar method was applied to the element for overcoming volumetric locking with simple elements [8]. The Coulomb friction rule was assumed and the coefficient of friction μ was determined as 0.07 according to the authors' previous research so that the analytical and experimental drawing force might be in good agreement [9].



Figuire 1: Tube drawing with plug

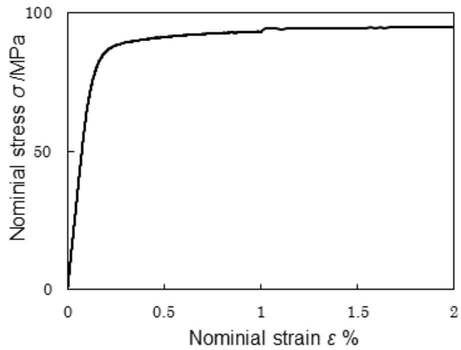


Figure 2: Stress-Strain diagram of 1050 aluminum

Table 1: Drawing condition

Die	Die hole diameter d_d /mm	30
	Die half angle θ /deg.	15
	Bearing length l_b /mm	4
Plug	Plug diameter d_p /mm	24
	Supporting rod length l_p /mm	50
Tube	Material of tube	A1070
	Tube outer diameter t_d /mm	31.5
	Tube thickness t_0 /mm	3.2
	Length of tube l_t /mm	170
Coefficient of friction μ	0.07	

3 FEM MODEL

3.1 EFFECT OF ELEMENT NUMBER AND SIZE IN 2D ANALYSIS

It is important to determine the minimum bare element number for shortening calculation time with maintaining analysis precision. The suitable element numbers and fineness in thickness and axial direction was determined in 2D analysis.

Firstly, the effect of element number in thickness direction was examined by fixing element length in axial direction as 0.5 mm. Table 2 shows drawing condition. Figure 3 shows comparison results on the axial residual stress as it is higher than the radial and hoop stresses. The element number in thickness ranged from 3 to 12, and the elements have the same size in both radial and axial directions. The minimum bare element number N_t is determined as 7, judging from the evenness of the axial residual stress distribution. When N_t is less than 7, the stress distribution is uneven. It is noteworthy that the stress distribution change in thickness direction is steep in the vicinity of the outside surface while it is moderate at the inside and that unevenness is noticeable at the outside when N_t is 5.

Therefore, finer elements should be applied near the outside surface. Figure 4 shows the effect of applying finer mesh near the outside surface for the thickness element number N_t =7. In Figure 4(a), 4 elements are equally fine and the other 3 elements are equally rough. In Figure 4(b), elements become gradually fine toward the outside surface, with length ratio $\Delta t_i/t_{i-1}$ of 0.97. While Figure 4(a) shows no improvement to the result of N_t =7 in Figure 3, Figure 4(b) shows further improved smooth results which is more similar to the result of N_t

=12 in Figure 3. Therefore, the optimum element number in thickness direction was determined as 7 with length ratio $\Delta t_i/t_{i-1}$ of 0.97.

Figure 5 shows the effect of element size in axial direction. The axial size ΔL/division ranged from 0.33 to 1 mm/division. Neither ΔL/div. = 0.33 mm/div. nor ΔL/div. = 1.0 mm/div. achieves better results than ΔL/div. = 0.5 mm/div. The condition of ΔL/div. = 0.5 mm/div. would be suitable for thickness element number N_t =7 with length ratio $\Delta t_i/t_{i-1}$ of 0.97, and this element size was adopted in the remainder part.

Table 2: Drawing condition of 2D axisymmetric model

Die	Type	Rigid
Plug	Type	Rigid
Tube	Type	Elasto-plastic
	Length of tube l_t /mm	50
	Initial thickness variation $\Delta t_0 = t_{0max} - t_{0min}$ /mm	0

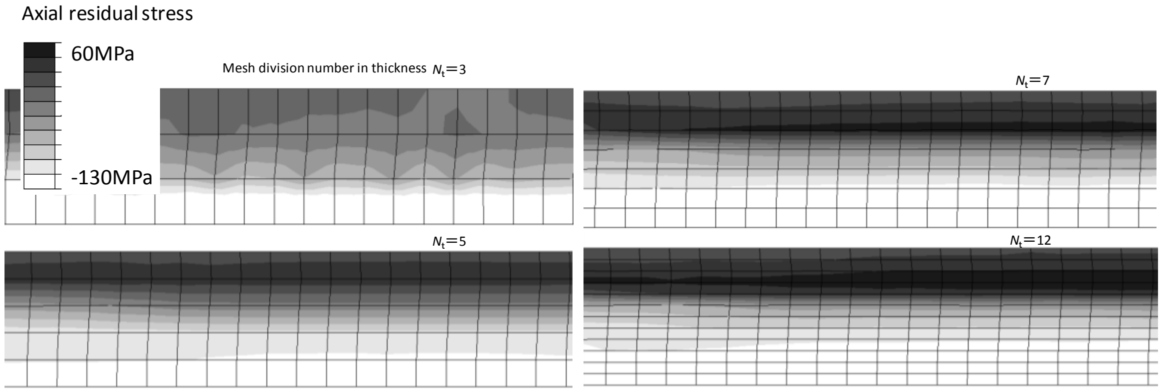


Figure 3: Influence of thickness element number on axial residual stress distribution (element size in axial direction is 0.5 mm per division)

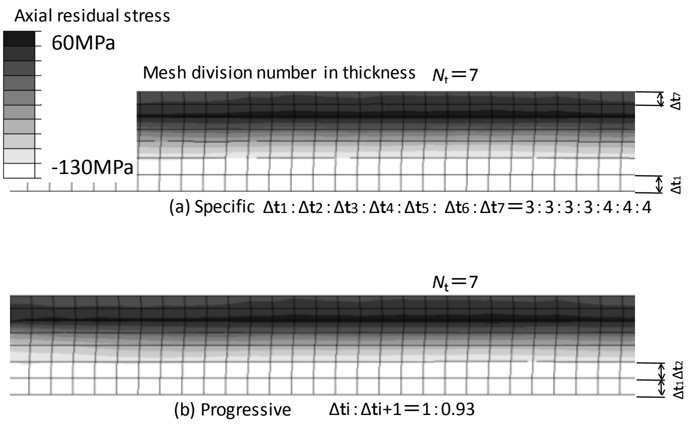


Figure 4: Influence of thickness element length ratio on axial residual stress distribution (thickness element number N_t = 7, element size in axial direction is 0.5 mm per division)

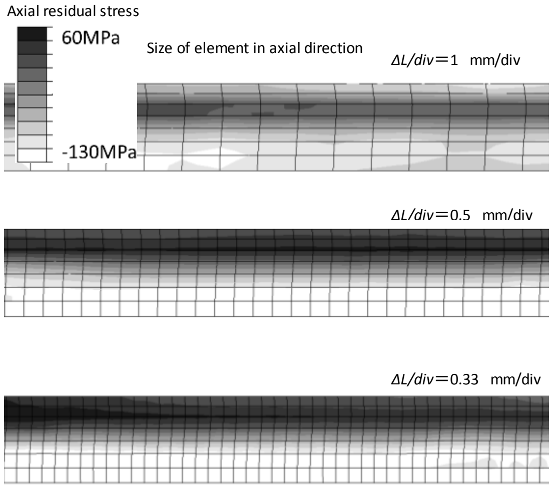


Figure 5: Influence of element size in axial direction on axial residual stress distribution

3.2 3D FEM MODEL

Figure 6 shows 3D FEM model, and Table 3 shows drawing condition. One half models were adopted considering symmetric property at Y-Z plane. The model was built up for simulation of tube drawing with a plug on a supporting rod. In the actual operation, the supporting rod is so long that the rod freely moves in directions vertical to axial direction. Instead of applying a long supporting rod, a short rod was modelled and the head end was constrained in the axial direction (Z axis), but not constrained in the vertical direction (Y axis). The tube was assumed to be elasto-plastic, and the plug and rod were elastic, while die was assumed to be rigid. The die inner and the plug outer surfaces were composed of many rectangles, and the nodes of tube were initially placed at the centre of the rectangles so that the nodes might be freely movable in hoop direction.

Table 3: Drawing condition of 3D model

Die	Type		Rigid
Plug	Type		Elastic
Tube	Type		Elasto-plastic
	Length of tube l_t /mm		150
	Initial thickness variation $\Delta t_0 = t_{0max} - t_{0min}$ /mm		0
	Division in FEM	Axial	0.5 mm/div
		Radial	7div $\Delta t_i : \Delta t_{i+1} = 1:0.93$
		Hoop	15 deg./div

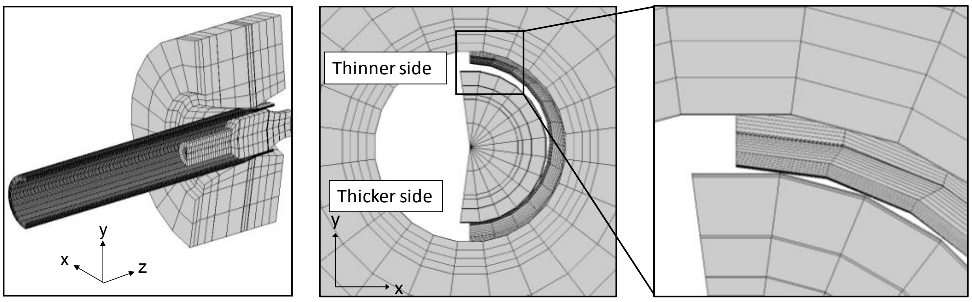


Figure 6: 3D FEM model

4. THE EFFECT OF THICKNESS VARIATION

Figure 7 shows thickness distribution along axial direction. The position l_a is defined as the distance from the boundary between taper and parallel part of tube initial shape as shown in Figure 1. When the position l_a was less than 100 mm, the tube thickness changed according to increase of l_a. The thickest part thickened with increase of l_a while the thinnest part thinned with increase of l_a. The thicknesses were stable at the tail side when l_a was larger than certain value, i.e. 130 mm for the both side.

Thickness after drawing was evaluated at the arrowed points in Figure 7 where thicknesses became stable, i.e. at l_a = 130 mm. Influence of initial thickness variation on thickness variation after drawing is shown in Figure 8. It is noteworthy that thickness variation increased after the drawing under the condition in Table 1 against intuition. Thickness of the thinnest side decreased, while that of the thickest side increased as shown in Figure 8(b) under the condition with light target thickness reduction α_T, which is defined by the following equation,

$$\alpha_T = \frac{t_{ave0} - (d_d - d_p)/2}{t_{ave0}} \quad (1),$$

where t_{ave0} is initial average thickness.

It is known that thickness variation generally decreases after tube drawing without plug [10]. Figure 9 shows the mechanism of this thickness change during tube drawing. When the tube is compressed in the radial and hoop directions at the die approach, compressive hoop stress is larger at the thinnest part than at the thickest part. As a result, the tube thickness increases larger at the thinnest part than at the thickest part and then thickness variation decreases. This mechanism is called "compressive hoop stress effect" in this paper.

On the other hand, the plug position determines the thickness variation in tube drawing with plug. The plug position is affected by "contact area effect" as well as "compressive hoop stress effect". Figure 10 shows a FEM results where the plug was fixed in the vertical direction so that the thickness reductions on the thickest and thinnest sides might be equal. Under this condition, the contact pressure should be almost the same on the thickest and thinnest sides as equivalent plastic strain should be almost the same. However, the contact length was larger on the thickest side than that on thinnest side as shown in Figure 10. As a result, the total contact force, which is obtained by integration of contact pressure by area, became larger on the thickest side than on the thinnest side, and then the plug moved toward the thinnest side resulting in further increase of thickness variation.

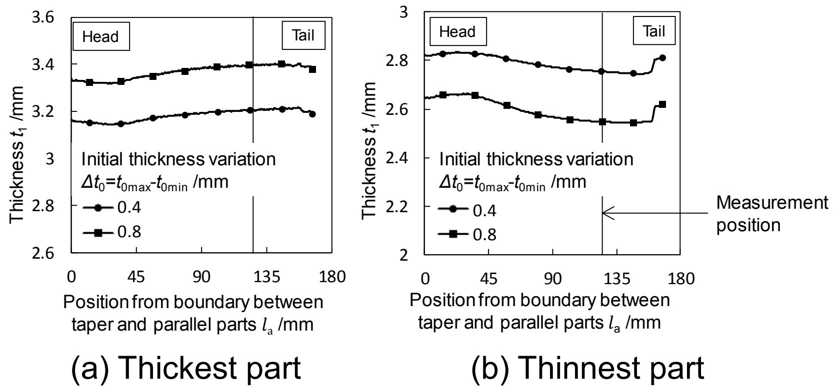


Figure 7: Thickness distribution of drawn tube

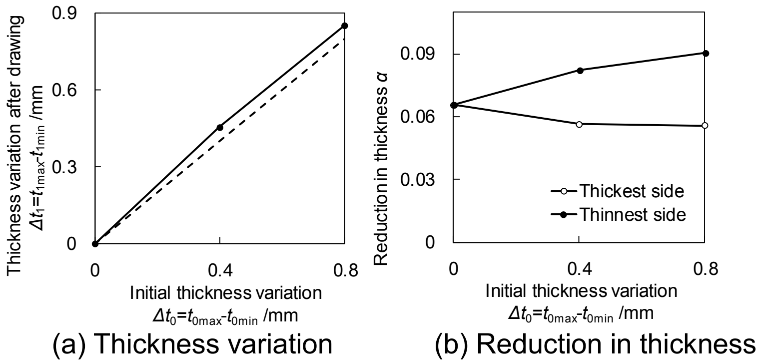


Figure 8: Influence of initial thickness variation on that after drawing

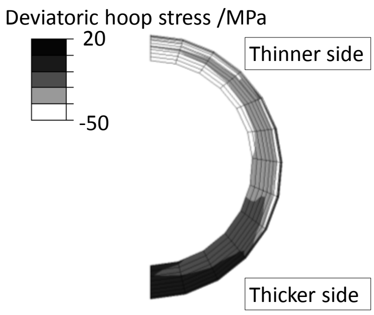


Figure 9: Hoop stress distribution

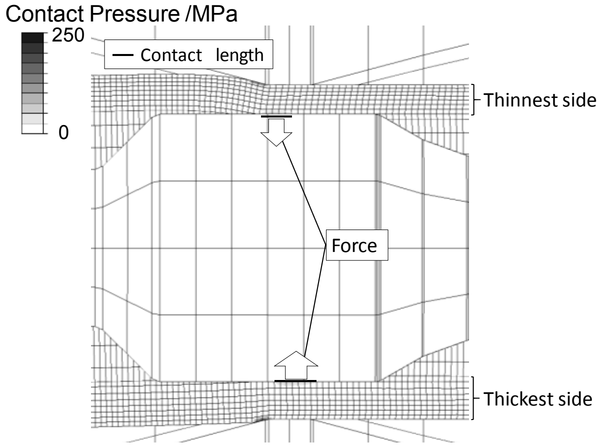


Figure 10: Influence of thickness deviation on contact length under the condition where plug is constrained in vertical direction to let the thickness reduction the same

5. CUVATURE BEHAVIOUR

The drawn tubes are not completely straight, and are slightly bent so that the thinnest part might be the extrados of the bending arc under the condition in Table 1 with light target thickness reduction. The mechanism of bending direction is explained by the volume constancy and the thickness variation change during drawing. As the thickness reduction is larger at the thinnest side than at the thickest side, the thinnest side elongates larger than the thickest side, and then the thinnest side becomes the extrados of the bending arc.

Figure 11 shows the effect of initial thickness variation on curvature, which is evaluated at the tail side where thickness is stable in Figure 7. The curvature increased with increase of initial thickness variation.

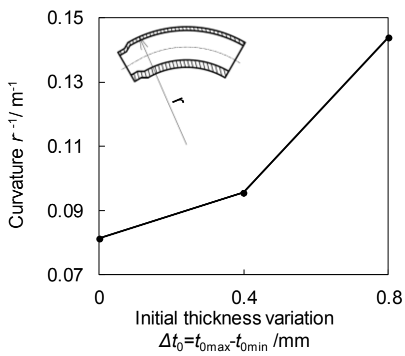


Figure 11: Effect of initial thickness variation on curvature

6. THE EFFECT OF TARGET THICKNESS REDUCTION

The effect of target thickness reduction α_T on thickness variation is investigated under the condition as shown in Table 4, where plug diameter changed for controlling target thickness reduction. Figure 12 shows the plug position change attendant upon the target thickness reduction. Plug position y is positive as the plug moves towards the thinnest side naturally. However, y decreased with increase of target thickness reduction α_T. Figure 13 shows effect of target thickness reduction α_T on thickness variation. Thickness variation Δt_1 decreased with increase of α_T. Even though Δt_1 is larger than initial one Δt_0 when target thickness reduction α_T is 6.25%, Δt_1 is less than Δt_0 when α_T is larger than 8.3%. It might be because "compressive hoop stress effect" might be stronger than "contact area effect" with increase of target thickness reduction α_T.

Table 4: Drawing condition for investigation of effect of target thickness reduction

Die	Type	Rigid
Plug	Type	Elastic
	Plug diameter d_p /mm	24, 24.2, 24.4, 24.6
Tube	Type	Elasto-plastic
	Length of tube l_t /mm	150
	Initial thickness variation $\Delta t_0 = t_{0max} - t_{0min}$ /mm	0.8
	Target thickness reduction α_T %	6.25, 9.375, 12.5, 15.625

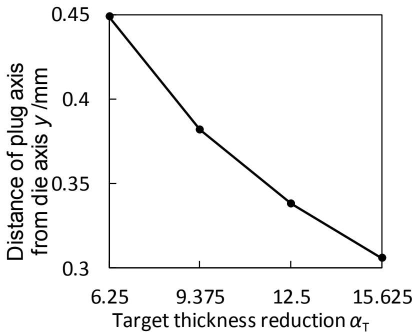


Figure 12: Effect of target thickness reduction on plug position

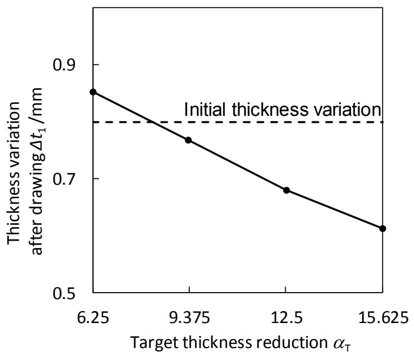


Figure 13: Effect of target thickness reduction on thickness variation

7. CONCLUSION

The present research clarified the effect of initial thickness variation and target thickness reduction on precision of cross section and straightness in tube drawing with plug inside, using 3D FE analysis. Firstly, a 3D FEM model was built up for the examination by optimizing the element size based on analytical results of 2D FEM. The 3D FE analysis revealed some noteworthy phenomena against intuition. There might be two mechanism which affect thickness variation. One is "contact area effect", and the other is "compressive hoop stress effect". The latter mechanism was also observed in tube drawing without plug. When the target thickness reduction was small, thickness variation increased after drawing as "contact area effect" was stronger than the other, by making the plug move towards the thinnest side. When the target thickness reduction was large, however, thickness variation decreased as "compressive hoop stress effect" was stronger than the other. Therefore, attention should be paid when tubes are drawn in light target thickness reduction as it might lead to increase of thickness variation. The drawn tube slightly bent according to the difference of thickness reductions of the thickest and thinnest sides.

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