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NUMERICAL ANALYSIS OF THE EFFECT OF FRICTION DURING FORMING OF TUBE WITH DIFFERENTIAL WALL THICKNESS

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Abstract. Steel tubes with differential wall thickness are required to reduce the weight of automobiles. One of the forming processes of steel tubes with differential thickness is the ironing of the inner surface. In the first process, the end of the steel tube is expanded. In the second process, the punch is pushed in and the inner surface of the steel tube is ironed. As a result, the steel tube with a wall thickness difference of 50% can be formed. In this report, the behavior of the steel tube during forming and the possible forming condition were clarified using FEM (Finite Element Method) analysis. Abaqus/Explicit was used for FEM analysis, and analysis was performed using an axisymmetric model. The friction coefficient between the steel tube and the punch μ_{P} is 0.00 to 0.20, and the friction coefficient between the die and the steel tube μ_{D} is 0.15 to 0.25. As a result of the analysis, it was found that the friction coefficient difference $\Delta\mu = \mu_{\mathrm{D}} - \mu_{\mathrm{P}}$ needs more than the threshold in order to form the steel tube with differential thickness. If $\Delta\mu$ is larger than the threshold, the steel tube is fixed at the expansion part, and the steel tube with differential thickness can be formed. On the other hand, if $\Delta\mu$ is smaller than the threshold, the expansion part is slipping during forming and the steel tube with differential thickness cannot be formed. This result suggests that the effect of the friction coefficient can be evaluated quantitatively using FEM analysis.

1 INTRODUCTION

In recent years, the automobile industry has been seeing increasing demand for reducing the weight of vehicles for the purpose of curbing carbon dioxide emissions. To ensure essential performance such as steering stability while reducing weight, studies have been carried out on the use of high-strength materials and appropriate arrangement of steel sheet thickness. In this context, one study reported various methods to form steel tubes with different wall thicknesses in the circumferential or longitudinal direction to appropriately arrange the wall thickness of tubular steel members [1].

Generally, methods to form steel tubes with differential thickness are divided into forming from sheets and forming from tubes. In forming from sheets, steel sheets with different thickness are welded to manufacture tailored blanks and they are formed into tubes. In forming from tubes, a common process is drawing but the maximum wall thickness difference it can achieve is 40% [2]. Further reduction of the weight of automobiles in the future will require steel tubes with much greater wall thickness differences and techniques to form such tubes.

To that end, this study focused on the process in which steel tubes with differential thickness are formed by partly ironing the inner surface of steel tubes [3]. The ironing process is a process performed using a steel tube as the starting material, where one side of the inner or outer surface of the tube is restrained using a die and the unrestrained side is ironed using a punch to reduce the wall thickness. A representative process of ironing is the outer ironing for cans in which cans are drawn then the outer surface is ironed. In the processing method discussed in this report, a steel tube with differential wall thickness is formed by inner ironing in which the outer surface of a steel tube is restrained and a punch is inserted along the inner surface of the steel tube to reduce the wall thickness. The authors have found that this processing method enables forming steel tubes with differential wall thickness with a wall thickness difference of 40% or greater without having any cracks or creases [4]. However, not many reports have been made about detailed studies on the forming conditions and necessary force for this processing method.

In this report, the authors studied the effects of lubrication conditions (friction coefficients) on the success/failure of forming and process loads in the forming of steel tubes with differential wall thickness by inner ironing through numerical analysis using the Finite Element Method (FEM).

2 MODEL OF NUMERICAL ANALYSIS

Fig. 1 shows a schematic illustration of the inner ironing process for forming steel tubes with differential wall thickness studied in this report. In the first process, while one end of a steel tube is secured with a stopper, an expanding punch is inserted from the other end to expand the tube. Then, in the second process, the stopper is removed, and an ironing punch is pushed into the tube while the part expanded in the first process is clinging onto the die to iron out the inner surface of the steel tube to make the wall thinner. The punch is inserted until the ironed part reaches the desired length. Lastly, the punch is withdrawn. While the punch is being withdrawn, the formed steel tube hits the scraper placed at the expanded tube side and dislodges itself from the punch. As a result of this forming, one obtains a steel tube with differential wall thickness comprising an expanded part (thick wall), ironed part (thin), and unformed part (thick).

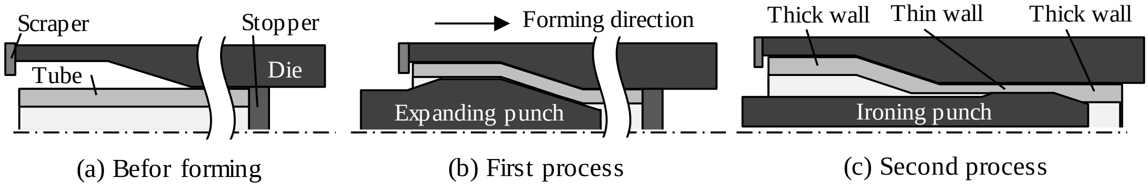


Fig. 1: Schematic illustration in ironing process

The sample tube used was an electric resistance welded steel tube with an outer diameter of 80 mm, wall thickness of 2.0 mm, and tensile strength of 440 MPa class (yield strength: 433 MPa, tensile strength: 524 MPa, total elongation: 29.9%).The assumed forming of steel tube with differential wall thickness was an ironing rate of 50% (wall thickness from 2.0 mm to 1.0 mm) and ironed part length of 70 mm, as shown in **Fig. 2**.

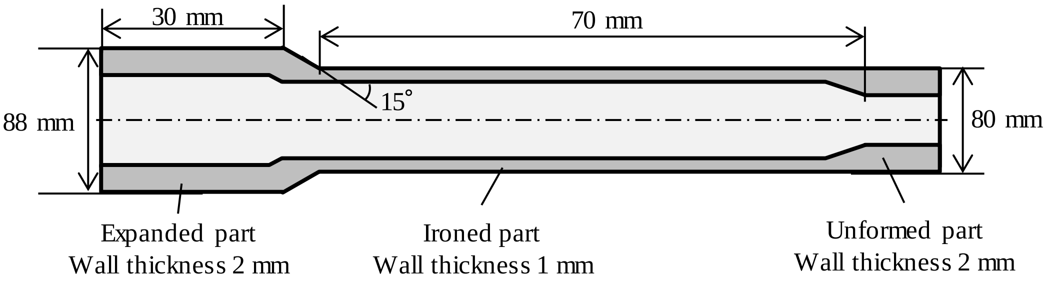


Fig. 2: Dimension of steel tube with different thickness

The general-purpose code Abaqus/Explicit version 6.14 was used for the FEM analysis. The steel tube was assumed to be a four-node axisymmetric element (CAX4R) with the element size of about 0.5 mm and quintisectioned radially. The die and punch were assumed to be analytic rigid bodies. **Fig. 3** and **Fig. 4** show the dimension of the die and punches used for the FEM analysis, respectively. The punches used in the analysis have a 1-mm clearance at the proximal side to prevent the process load from increasing due to the punches getting seized by the tube during the forming.

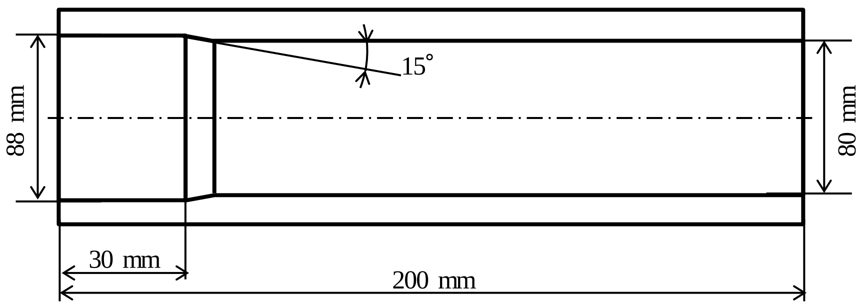


Fig. 3: Dimension of die used for analysis

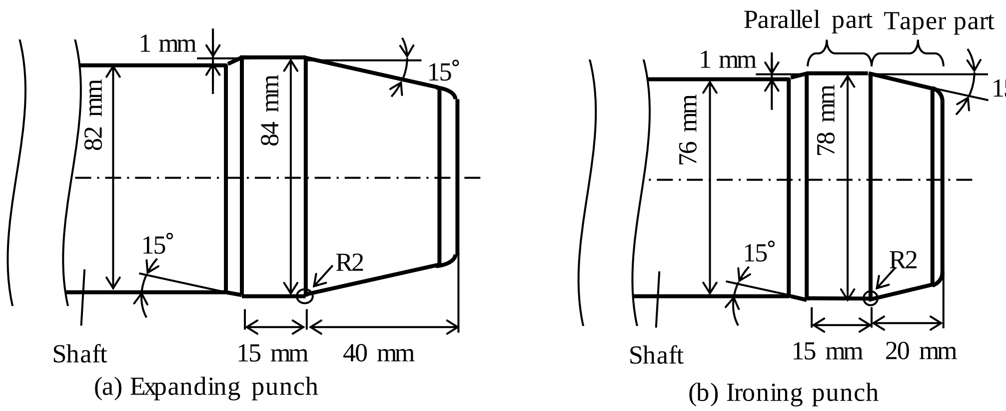


Fig. 4: Dimension of punches used for analysis

The lubrication conditions assumed were non-lubrication and use of pressing oil, and the static friction coefficient between the steel tube and the punch, μ_{P}, was 0.00 to 0.25 and that between the die and the steel tube, μ_{D}, was 0.10 to 0.25. In order to keep the steel tube in place during forming, the relationship $\mu_{\mathrm{D}} > \mu_{\mathrm{P}}$ was maintained. Hereinafter, the difference between the static friction coefficients, $\mu_{\mathrm{D}} - \mu_{\mathrm{P}}$, is expressed as $\Delta\mu$. As the material characteristic, the stress-strain diagram obtained through a uniaxial tensile test using a JIS 12B arc test piece was used after normalizing using equation (1) and parameters shown in **Table 1** [5]. Also, the von Mises yield stress formula was applied. The boundary conditions were restriction of three degrees of freedom for the die and restriction of two degrees of freedom except the longitudinal translational movement for the punches. In addition, to simulate the restriction with the stopper, the end of the tube secured with the stopper was fully restrained in the first process, and the restraint was removed from the second process onward.

$$\sigma = K(\varepsilon^p + a)^{\{\bar{n}+1/b(\varepsilon^p+c)\}} \tag{1}$$

Table 1: Value of each parameter

K [MPa]	$\bar{n}$	a	b	c
784	0.136	0.0136	0.305×10^6	0.00202

3 RESULTS OF NUMERICAL ANALYSIS

Fig. 5 shows the behavior of steel tube during ironing at a static friction coefficient between steel tube and punch, $\mu_{\mathrm{P}} = 0.10, 0.15$, and 0.20, and that between die and steel tube, $\mu_{\mathrm{D}} = 0.20$. The behavior was compared for the range enclosed by broken lines shown in Fig. 5(a). For clarity, the dimension in the radial direction was doubled compared with that in the longitudinal direction. The behavior was checked for every 10 mm of stroke, with the ironing starting point set as stroke 0 mm. The distance the expanded part end of the tube moved in the longitudinal direction during the ironing is shown below Fig. 5(b) to (d) as a slip of the steel tube.

Under the conditions of $\mu_{\mathrm{D}} = 0.20$ and $\mu_{\mathrm{P}} = 0.10$ (Fig. 5(b)), the steel tube was secured at the expanded part during ironing and the ironing process completed without slipping. The desired steel tube with differential wall thickness was obtained in the end. Hereinafter, conditions under which the steel tube behaved in this manner are indicated by a circle (○). Under the conditions of $\mu_{\mathrm{D}} = 0.20$ and $\mu_{\mathrm{P}} = 0.15$ (Fig. 5(c)), the steel tube started to have a gap from the die at a stroke of 30 mm, and slipping of the steel tube occurred during ironing. In the end, a slip of 15 mm occurred at the expanded part end of the tube, and the desired steel tube with differential wall thickness could not be formed. Hereinafter, conditions under which ironing was possible at the initial stage of forming but slipping occurred during forming and the amount of slip at the end was less than 30 mm are indicated by a triangle (△). Under the conditions of $\mu_{\mathrm{D}} = 0.20$ and $\mu_{\mathrm{P}} = 0.20$ (Fig. 5(d)), slipping occurred at the initial stage of ironing, and the desired steel tube with differential wall thickness could not be formed. Hereinafter, conditions under which slipping occurred at the initial stage of forming and the amount of slip at the end was 30 mm or more are indicated by a cross (×).

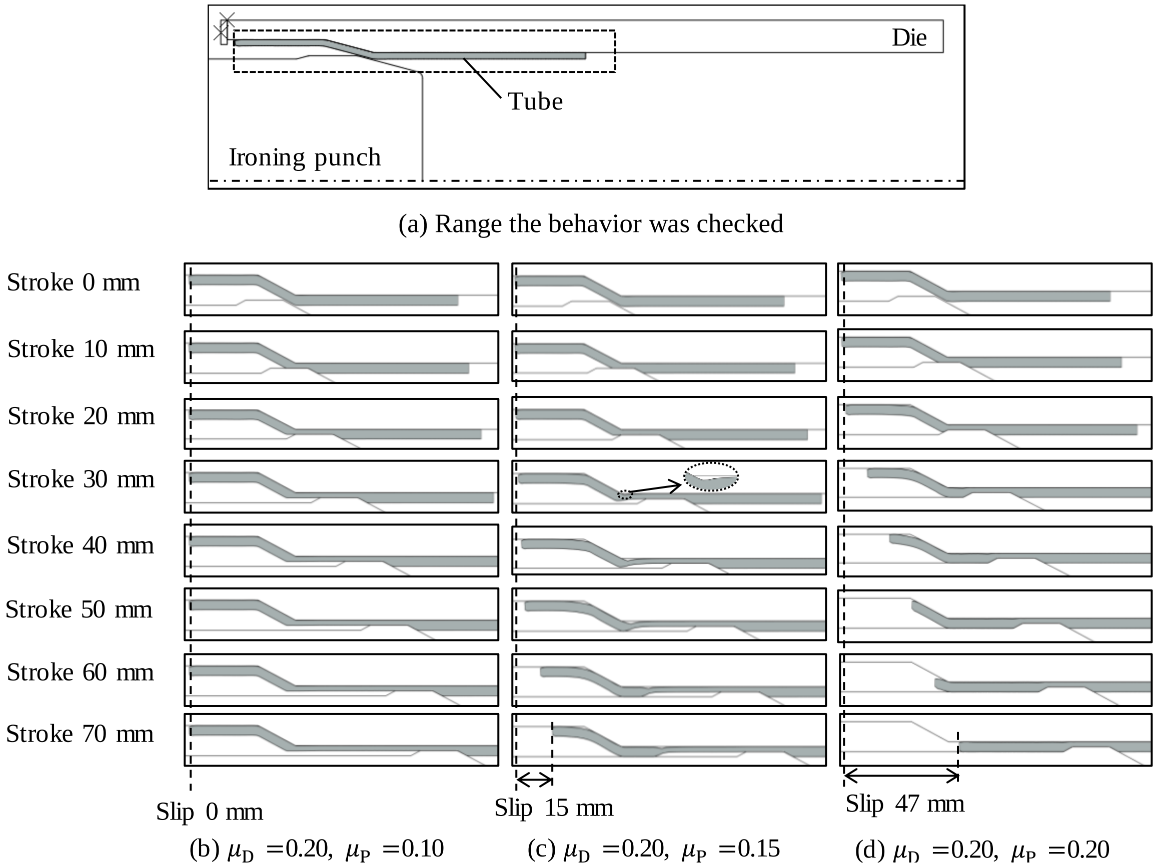


Fig. 5: Behavior of steel tube during ironing. Comparison was made for the range enclosed by broken lines shown in (a). The dimension in the radial direction was doubled compared with that in the longitudinal direction in (b) to (d). For the stroke, the ironing starting point was set as 0 mm. The slip of the steel tube is the distance the expanded part end of the tube moved in the longitudinal direction during the ironing, which is shown below (b) to (d).

Fig. 6 shows a chart of μ_D plotted against μ_P, in which the behavior of steel tube during forming is indicated by different marker shapes. The broken line in the figure indicates $\Delta\mu = 0.05$. The figure shows that slipping of the steel tube does not occur and the desired steel tube with differential wall thickness is successfully formed when μ_D is large and μ_P is small. The figure also shows that forming was successful at $\Delta\mu > 0.05$ while slipping occurred at $\Delta\mu \leq 0.05$, indicating that $\Delta\mu = 0.05$ is the threshold of successful forming. The authors have found that $\Delta\mu = 0.08$ was the threshold of successful forming when steel tubes with differential wall thickness were formed using different dies [6]. From the above, it can be assumed that dies with smaller $\Delta\mu$, the threshold of successful forming, realize easier forming of steel tubes with differential wall thickness by ironing.

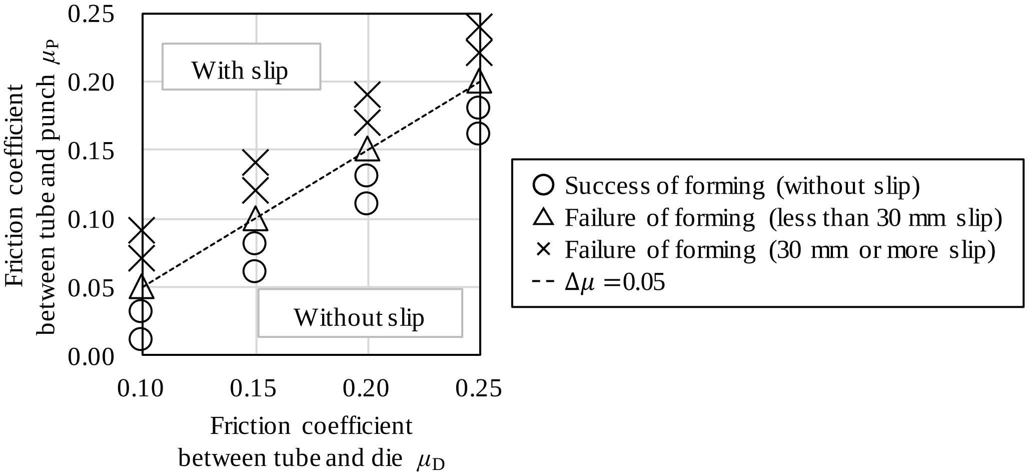


Fig. 6: Success/failure of forming under various conditions. The broken line indicates $\Delta\mu = 0.05$.

Fig. 7 shows the relationship between the process load and punch stroke when μ_P is fixed and μ_D is changed. **Fig. 8** shows the relationship between the process load and punch stroke when μ_D is fixed and μ_P is changed. In both cases, comparison was made for the conditions under which the desired steel tube with differential wall thickness was successfully formed. The process load was specified as a total of the force that applies to the ironing punch in the longitudinal direction at a certain punch stroke, plotted every 5 mm of punch stroke. The punch stroke of 0-5 mm is the range where the taper part of the punch passed through the expanded part of the die and tube and started ironing, and the process load increased significantly. The punch stroke of 5-15 mm is the range where the parallel part of the punch passed through the expanded part of the die and tube, and the process load increased almost linearly. After the punch stroke of 15 mm, the process load remained almost constant. Note that, in the case of $\mu_P = 0.00$, there is no friction force between the punch and steel tube and therefore the load did not change after 5 mm.

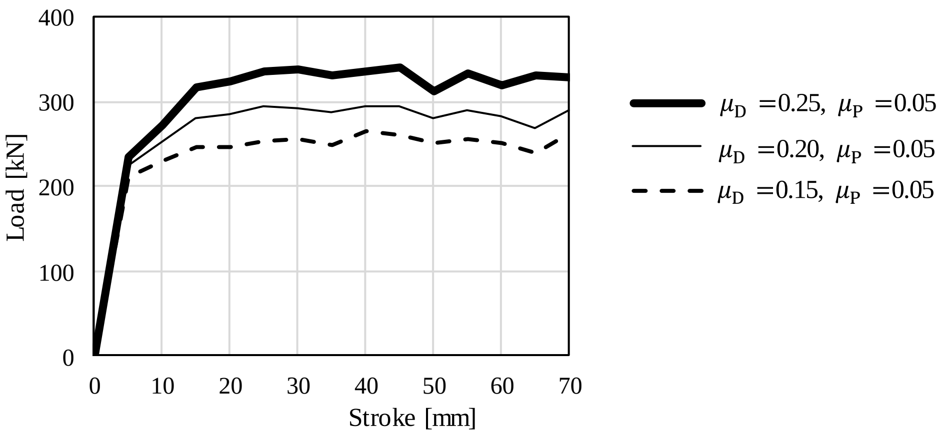


Fig. 7: Relationship between process load and punch stroke at $\mu_P = 0.05$

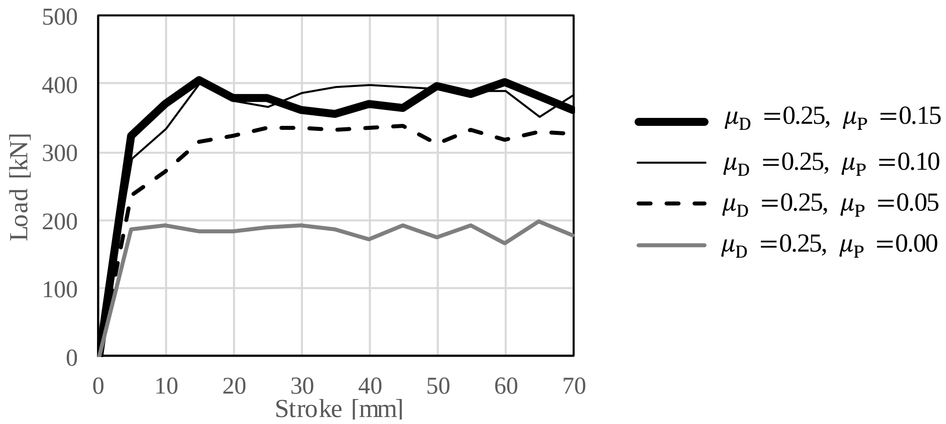
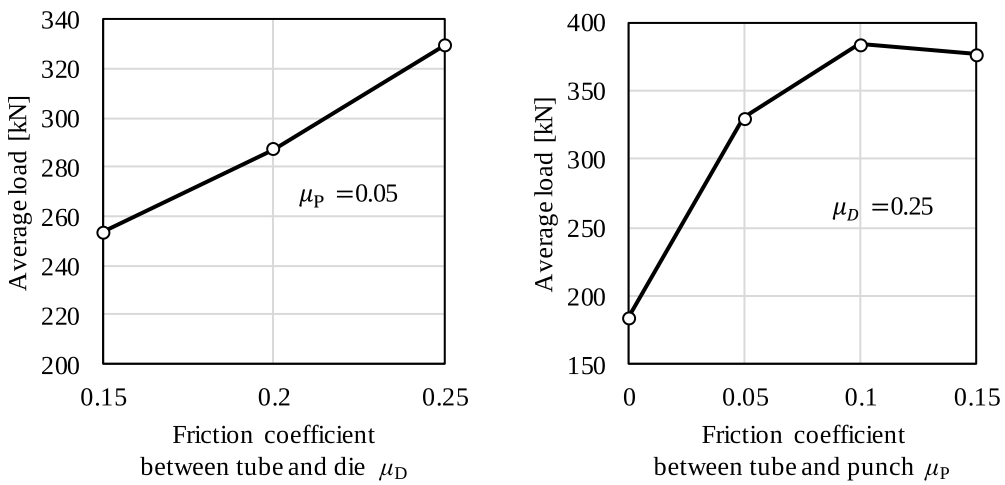


Fig. 8: Relationship between process load and punch stroke at $\mu_{\mathrm{D}} = 0.25$

Fig. 9 shows the relationship between the friction coefficients and the process load averaged over the stroke of 15-70 mm where the process load remained unchanged. Fig. 9(a) indicates that the process load increased almost linearly with μ_{D}. Regarding at which stage of forming the process load increased, Fig. 7 showed that the process load greatly increased in the stroke range of 5-15 mm where the parallel part of the punch started ironing. Fig. 9(b) shows that the process load tends to increase as μ_{P} increases, but the process load at $\mu_{\mathrm{P}} = 0.15$ is similar to that at $\mu_{\mathrm{P}} = 0.10$. Regarding at which stage of forming the process load changed, Fig. 8 showed that, at a stroke of 5 mm, the process load was larger when μ_{P} was larger. Meanwhile, in the stroke range of 5-15 mm where the parallel part of the punch started ironing, the amount of increase in the process load became smaller as μ_{P} increased.



(a) μ_{D} and average process load   (b) μ_{P} and average process load

Fig. 9: Relationship between friction coefficient and process load averaged for stroke range of 15-70 mm

4 DISCUSSION

First, the mechanism to determine the success/failure of forming by $\Delta\mu$ is to be theoretically discussed assuming the model shown in **Fig. 10** for the distal end of the punch during ironing. In the figure, F_{T1} is the normal force applied to the steel tube at the taper part of the punch, F_{T2} the normal force applied to the steel tube at the parallel part of the punch, μ_1 the friction coefficient between the punch and the steel tube, F_{D1} the normal force applied to the steel tube contacting the die corresponding to F_{T1}, F_{D2} the normal force applied to the steel tube contacting the die corresponding to F_{T2}, μ_2 the friction coefficient between the die and the steel tube, and F_{D3} is the z-direction force applied at the expanded part. In Fig. 10, the force that applies to the surface of the steel tube contacting the punch induces slipping of the steel tube, while the force that applies to the surface of the steel tube contacting the die suppresses slipping of the steel tube. The difference between the force that induces slipping of the steel tube and the force that suppresses slipping of the steel tube is expressed by equation (2). In equation (2), F_{T1z} is the longitudinal component of F_{T1} and F_{T1r} the radial component of F_{T1}.

$$F_{\mathrm{T1z}} + F_{\mathrm{T1r}} \times \mu_1 + F_{\mathrm{T2}} \times \mu_1 - F_{\mathrm{D1}} \times \mu_2 - F_{\mathrm{D2}} \times \mu_2 - F_{\mathrm{D3}} \tag{2}$$

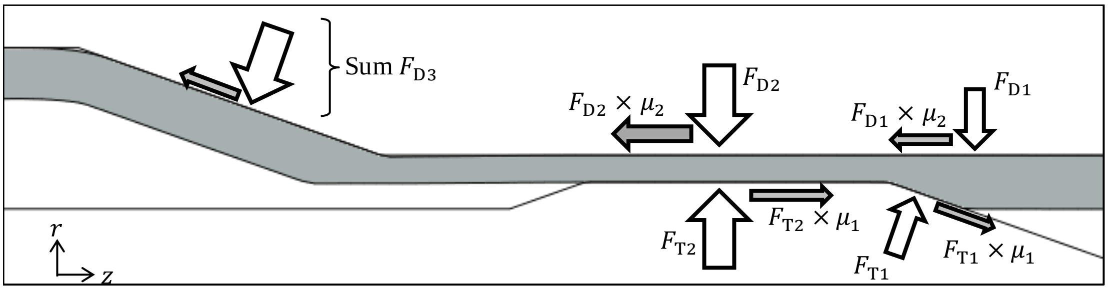


Fig. 10: Schematic illustration of force acting at the distal end of punch during ironing. F_{T1} is the normal force applied to the steel tube at the taper part of the punch, F_{T2} the normal force applied to the steel tube at the parallel part of the punch, μ_1 the friction coefficient between the punch and the steel tube, F_{D1} the normal force applied to the steel tube contacting the die corresponding to F_{T1}, F_{D2} the normal force applied to the steel tube contacting the die corresponding to F_{T2}, μ_2 the friction coefficient between the die and the steel tube, and F_{D3} is the *z*-direction force applied at the expanded part.

Assuming that F_{D1} and F_{D2} are the same as F_{T1r} and F_{T2}, respectively, when ironing can be performed without slipping, μ_1 is the same as μ_{P} and μ_2 is smaller than μ_{D}. On the contrary, when slipping of the steel tube occurs, μ_1 is smaller than μ_{P} and μ_2 is the same as μ_{D}. Therefore, at the critical point of the success/failure of forming, μ_1 and μ_2 are the same as μ_{P} and μ_{D}, respectively. In addition, since ironing of the steel tube can be performed without slipping when the force to suppress the slipping of the steel tube is greater than the force to induce the slipping, it can be said that slipping of the steel tube does not occur and the desired steel tube with differential wall thickness is successfully formed when equation (3) is satisfied.

$$F_{\mathrm{T1z}} + F_{\mathrm{T1r}} \times \mu_{\mathrm{P}} + F_{\mathrm{T2}} \times \mu_{\mathrm{P}} - F_{\mathrm{T1r}} \times \mu_{\mathrm{D}} - F_{\mathrm{T2}} \times \mu_{\mathrm{D}} - F_{\mathrm{D3}} \leq 0 \tag{3}$$

Rearranging equation (3) using $\Delta\mu$ gives equation (4).

$$-F_{\mathrm{T1z}} + (F_{\mathrm{T1r}} + F_{\mathrm{T2}}) \times \Delta\mu + F_{\mathrm{D3}} \geq 0 \tag{4}$$

Equation (4) indicates that the desired steel tube with differential wall thickness is successfully formed when $\Delta\mu$ is large. The above validates the finding that the success/failure of forming can be determined by $\Delta\mu$ obtained from analysis results.

Second, a change in the process load calculated from a theoretical formula for when the friction coefficient is changed is discussed based on analysis results. The process load is expressed by equation (5) when no slipping occurs for the steel tube.

$$F_{\mathrm{T1z}} + F_{\mathrm{T1r}} \times \mu_{\mathrm{P}} + F_{\mathrm{T2}} \times \mu_{\mathrm{P}} \tag{5}$$

Since $F_{\mathrm{T1z}} + F_{\mathrm{T1r}} \times \mu_{\mathrm{P}}$ is equivalent to the process load at a stroke of 5 mm, as shown in Fig. 7 and Fig. 8, it is independent of μ_{D} and increases as μ_{P} increases. Also, F_{T2} is calculated as the surface pressure applied to the parallel part of the punch multiplied by the area of the parallel part of the punch. In the analysis model used in this study, the area of the parallel part of the punch is constant and therefore F_{T2} is proportional to the surface pressure applied to the parallel part of the punch. In the model assumed in this study, because the relationship between the surface pressure applied to the parallel part of the punch and the friction coefficient is unclear, the relationship was estimated from the results of the analysis. **Fig. 11** shows the relationship between the surface pressure applied to the parallel part of the punch and the friction coefficient. The surface pressure applied to the parallel part of the punch used in this analysis was the average surface pressure for the range at which the parallel part of the punch contacted the steel tube at a stroke of 35 mm. Fig. 11(a) indicates that the surface pressure increases almost linearly with μ_{D}. Therefore, when μ_{P} is secured, similar to the surface pressure, the process load increases almost linearly with μ_{D}. Fig. 11(b) shows that the process load decreased linearly as μ_{P} increased. Meanwhile, the friction force that acts longitudinally increases compared with the surface pressure as μ_{P} increases. Therefore, when μ_{P} is small, since the amount of increase in the process load at the taper part is large, the process load increases with μ_{P}. However, when μ_{P} is large, the decrease in the process load due to a decrease in the surface pressure at the parallel part matches the increase in the process load at the taper part, and the process load no longer increases even when μ_{P} becomes larger. Fig. 9 supports these results.

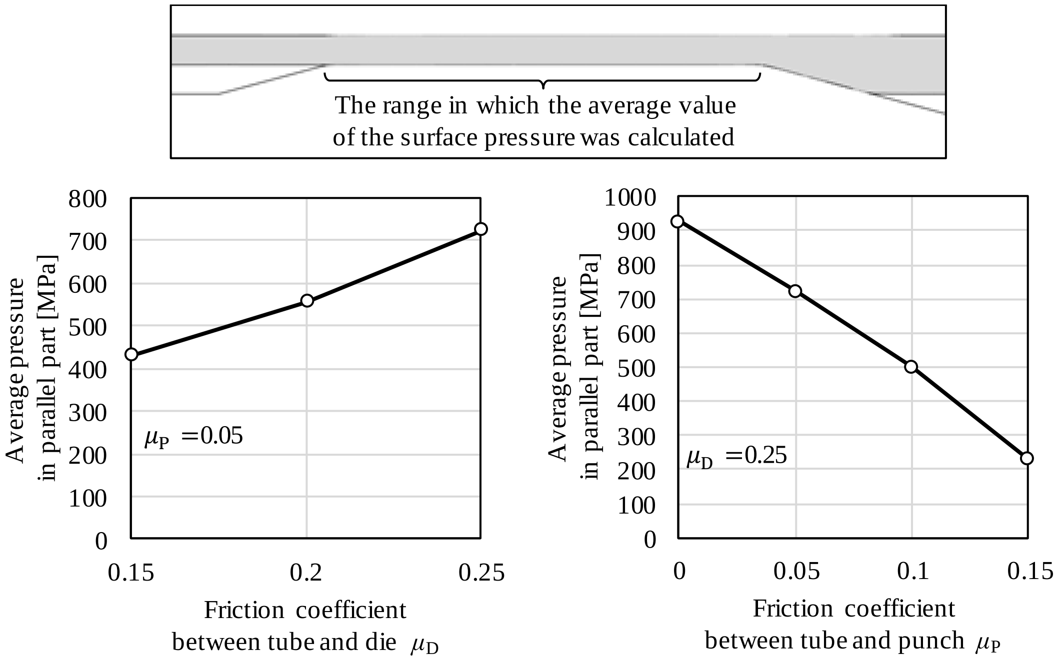


Fig. 11: Relationship between average surface pressure applied to the parallel part of the punch and friction coefficient at a stroke of 35 mm

5 CONCLUSION

In this report, the authors studied the effects of friction coefficients on the success/failure of forming in the forming of steel tubes with differential wall thickness by inner ironing through numerical analysis using the Finite Element Method. The obtained findings are:

- successful forming of steel tubes with differential wall thickness requires a certain amount of $\Delta\mu$ ($\mu_D - \mu_P$), the difference between the friction coefficient between the die and the steel tube, μ_D, and that between the punch and the steel tube, μ_P;
- the process load increased almost linearly with μ_D; and,
- when μ_P is large, the process load increases with μ_P because the surface pressure applied at the parallel part of the punch decreases almost linearly, but the amount of increase becomes smaller as μ_P further increases and the process load reaches a plateau at a certain μ_P.

Future studies include elucidation of the relationship between the friction coefficients and the normal force that applies at the taper and parallel part of the punch and the effects of other factors, such as the shape of the punch, on forming.

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