

Article

Effect of Roller Axial Position and Thickness on a Twisted Angle in the Twist Rolling of Aluminum Alloy 1050 Sheet Metal

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Abstract: This paper proposes a new rolling method called “twist rolling” that can continuously form a twisted shape by using taper rollers. The twisted shape of metal sheets is widely used in industrial products such as turbine blades and propellers. Such a shape is normally formed by casting or machining, but there are problems with low efficiency regarding the productivity and yield ratio. Forging processes have also been proposed, but they have problems with the surface property. The present study focuses on rolling to efficiently form a continuously twisted shape. The effect of the axial position of the taper rollers and skew angle on the average specific twisted angle were investigated by experiments and finite element analysis. The relationship between the thickness of sheet metal and the average specific twisted angle was also investigated. The average specific twisted angle decreased as the axial position increased. When the skew angle was smaller and the sheet metal thicker, the average specific twisted angle increased more. Twist rolling can form various twist angles by changing such parameters.

Keywords: taper roller; twisting; rolling; skew angle; sheet metal

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1. Introduction

Twisted metal products are used in many industrial fields and are often used in products such as propellers and turbine blades. These twisted products are often manufactured by machining, casting, or forging [1,2]. The forging process is a kind of plastic working and has many advantages compared with machining and other processing methods; for example, a higher production efficiency and less material loss. Makiyama et al. [3] proposed a new forging method called “twist forging”, in which two crossed bar-shaped tools are arranged to form a twisted shape by incremental line forging. This processing method forms various twisted shapes only by controlling the position of the die and workpiece. Hirt et al. [4] similarly proposed a process for bending sheet metal into the same plane using bar-shaped tools. Although the machine structure for this type of process is simple, there are some problems. For example, surface properties, such as unevenness left on the surface due to the hitting process, as well as low productivity.

The present study focuses on a rolling method in which the axis of the roll is skewed. Rolling [5] is a highly productive processing method used for not only reducing sheet thickness [6], but also for improving surface properties. Various rolling methods have been proposed to skew the axis of rotation of the rolls. For example, skew rolling, in which the axis of rotation is skewed in the rolling plane [7], suppresses defective phenomena [8] such as ear elongation and mid-elongation during rolling. Kuboki et al. [9] placed the rollers at a skew angle with the axis of material movement in the wire rod reduction process using concave rolls. The method arbitrarily reduces the diameter of the wire rods by adjusting the roll gap. This processing method not only corrects circularity, but can also process wires as thin as 0.6 mm in diameter. Yamane et al. [10] also studied skew rolling, which reduced

the outside diameter of a tube by applying shear strain to the tube between drum-shaped rollers with its axis skewed towards the rolling direction to make the material flow.

The above skew rolling methods may inevitably cause twisting deformation in the material, which can be problematic, and there are few precedents for effective use of this phenomenon. The present study proposes a new processing method called “twist rolling” in which twisted shapes are continuously formed using taper rollers. A previous study [11] investigated the qualitative trends of the average specific twisted angle in relation to three parameters, roller taper angle, skew angle, and sheet metal thickness, through experiments and finite element analysis (FEA). In this paper, the effects of the axial position of the roller and the skew angle on the twisted angle were investigated through experiments and analyses. The relationship between the sheet metal thickness and the twisted angle was also clarified.

2. Proposal of Twist Rolling

2.1. Structure and Principle

The structure and principle of the proposed method is shown in Figure 1. The rollers are divided into straight and taper sections. A pair of these rollers is placed at the top and bottom at the skew angle. The taper rollers are off-set from the origin of the coordinate by the axial position δ . The appearance of the rolled sheet metal is shown in Figure 2.

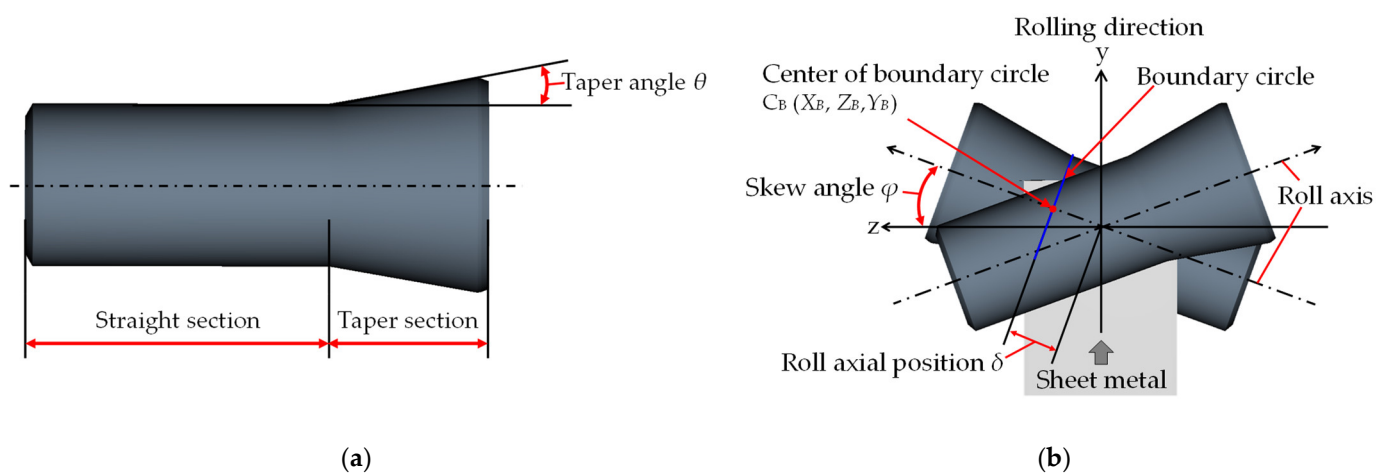


Figure 1. Structure and principle of the processing machine: (a) taper roller and (b) roller arrangement.

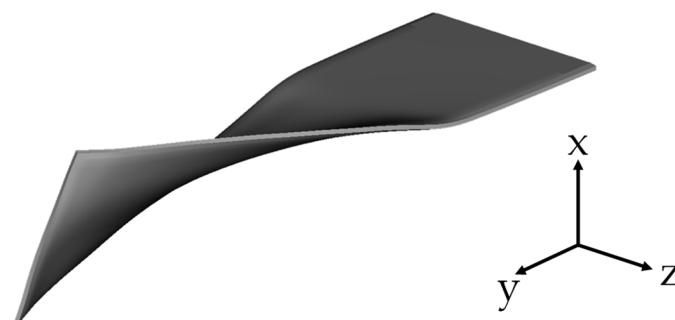


Figure 2. Twisted sheet metal.

Formed product was used for the following products. The twisted metal was used as a propeller blade. The surface of the formed metal was polished, and several pieces were welded to the shaft, and then they were used as propeller blades. The twisted metal was also used as a turbine blade. When the final shape was complicated, the twist rolling needed to be a “near-net shape” process, and the twisted metal needed to be subjected to

rough machining and surface finishing. It was also assumed that it could be used for liquid stirring components, heat exchangers, and so on.

2.2. Schematic of Experimental Machine

Figure 3 shows dimensions of the roller. The diameter of the roller straight section was 40 mm and the length was 80 mm. The angle of the taper section was 10° and the length was 40 mm. Table 1 shows the experiment conditions and Figure 4 shows the schematic of the experimental machine. The servomotor moved the pushing apparatus via the ball screw and the apparatus pushed the sheet metal into the gap between the rollers. The rollers were idle, not driven by a motor. They were rotated by the friction from the contact surface and fixed to the bearings in the experiment. The guide prevented the sheet metal from warping and buckling. Table 2 shows the (Z_B, Y_B) coordinates of each roll for each axial position δ . The point $C_B (X_B, Z_B, Y_B)$ denotes the point of the center of the boundary circle between the straight and taper sections, as shown in Figure 1b.

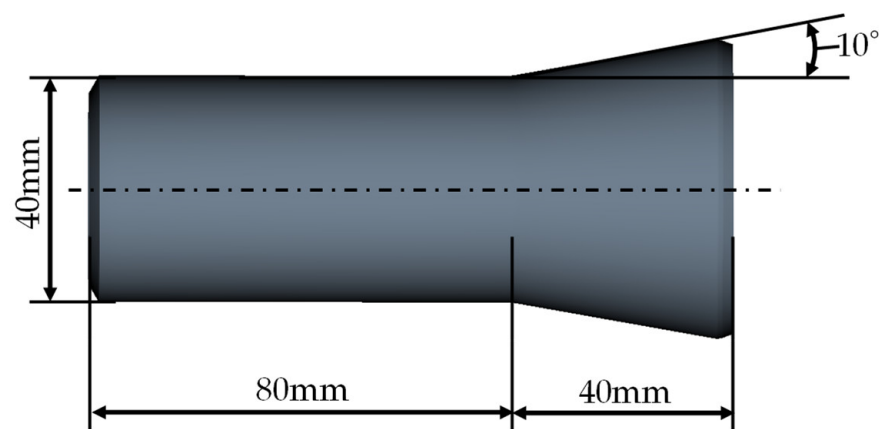


Figure 3. Dimensions of the roller.

Table 1. Experiment conditions.

Parent Sheet Metal	Material	Aluminum alloy 1050 (AA1050)
	Thickness t /mm	1, 2, 3
	Breadth b /mm	60
Roller	Material	SKD11
	Taper angle $\theta/^\circ$	10
Positioning	Skew angle $\varphi/^\circ$	10, 20
	Axial position δ /mm	10, 15, 20, 25
	Gap between rollers h /mm	Equal to sheet metal thickness t

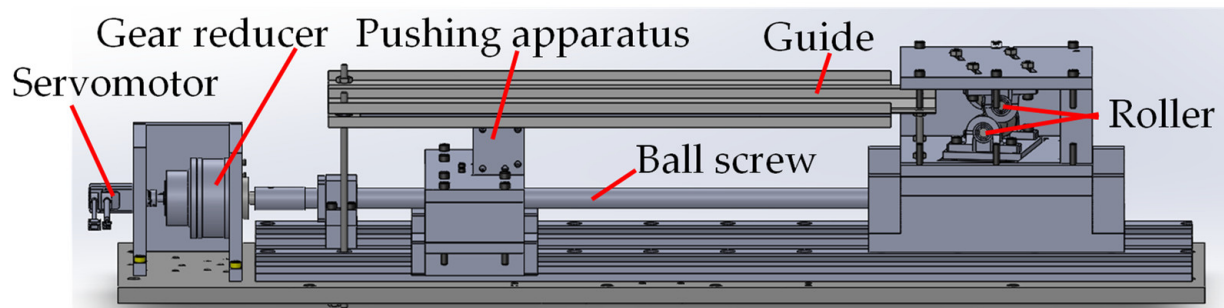


Figure 4. Schematic diagram of the experimental machine.

Table 2. (Z_B , Y_B) coordinates in each condition.

		Skew Angle $\phi/^\circ$	
		10	20
Roll Axial Position δ/mm	10	(± 9.85 , 1.74)	(± 9.40 , 3.42)
	15	(± 14.8 , 2.60)	(± 14.1 , 5.13)
	20	(± 19.7 , 3.47)	(± 18.8 , 6.84)
	25	(± 24.6 , 4.34)	(± 23.5 , 8.55)

(+ sign for lower roll, – sign for upper roll).

3. Experimental and Analytical Methods

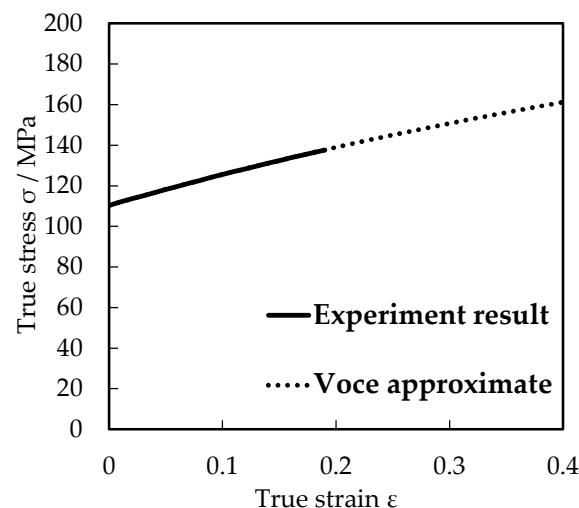
3.1. Sheet Metal and Properties

Aluminum alloy 1050 (AA1050) was used as the work material because it has good processing characteristics. The sheet metal was cut using a shearing machine to 60 mm width and 800 mm length. AA1050 was subjected to heat-treatment H24, which is specified by H4000 in Japan Industrial Standard (JIS). The mechanical properties of AA1050 are shown in Table 3 and the true stress–strain diagram is shown in Figure 5. True stress–strain diagrams were approximated by Voce’s equation and used in the analysis. The Voce law is shown in Equation (1) and the values of the parameters are shown in Table 4. A universal tensile–compression test machine, Shimadzu Autograph (AG-300kNXplus), was used for the tensile testing. The shape of the specimen was determined as in JIS Z2241.

$$\sigma = Y_\infty - (Y_\infty - Y_0)e^{(-h\varepsilon)} \quad (1)$$

Table 3. Mechanical properties of AA1050.

Young’s Modulus E/GPa	Poisson’s Ratio
70.3	0.33

**Figure 5.** True stress–strain diagram.**Table 4.** Value of the parameters in Voce law.

	Y_∞/MPa	Y_0/MPa	h
Value	239	129	1.25

3.2. Experiment and Analysis Conditions

Figure 6 shows the FEA model and the machine shown in Figure 4 was used for the experiment. As twist rolling is a new forming method, it is necessary to clarify the

mechanism of the rollers on the sheet metal. This processing method involves complex plastic deformation at the taper section of the roll, so it is difficult to investigate the effects of the forming conditions on formability only using experiments. The analysis enabled us to observe the deformation behavior of the sheet metal, which was not possible in the experiments. Therefore, in this study, in addition to the experiments, an analytical study was conducted. A commercial code, ELFEN, was used for the FEA and a static implicit scheme was adopted. In the analysis, the sheet metal length was 160 mm. The number of elements was 9408 and they were eight-node hexahedral elements. The sheet metal was divided into 28 divisions in the width direction and 88 divisions in the rolling direction. Each division was approximately 2.8 mm in the width direction and 1.9 mm in the rolling direction. The number of divisions was made finer at the edge of the sheet metal. The roller was set as a rigid body and sheet metal was an elasto-plastic body. Forming was performed by pushing from behind the sheet metal. The rotational speed of the roller was set so that the peripheral speed of the surfaces of the roller-straight section were equal to the pushing speed. In experiment, sheet metal length was 800 mm and the sheet metal was pushed by 500 mm. The taper angle of each roller was 10° . A pair of rollers was positioned at the skew angle φ .

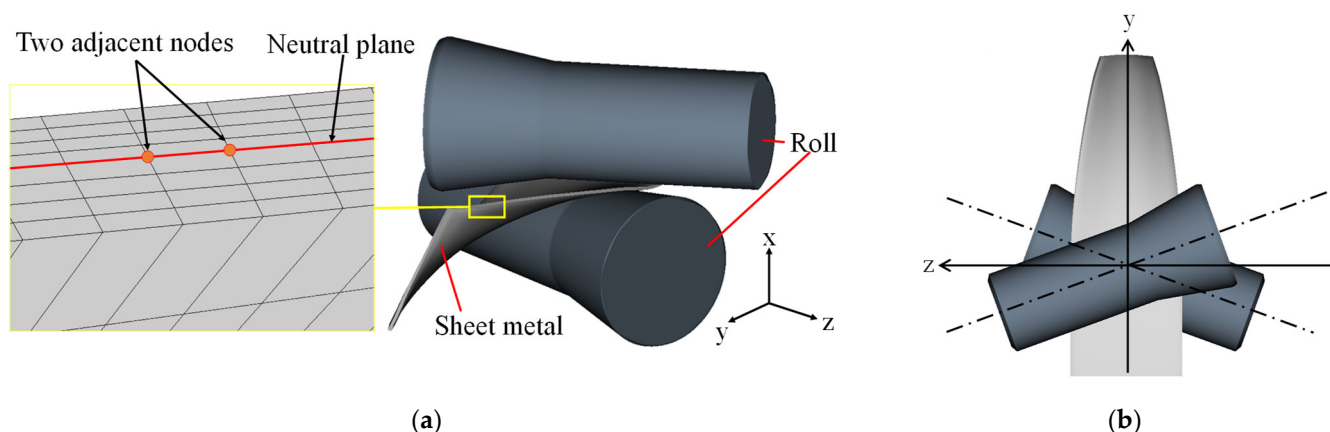


Figure 6. FEA model: (a) diagonal view and (b) top view.

3.3. Evaluation Items and Method

In the present study, the average specific twisted angle $\bar{\beta}$ was used for the evaluation of twist. In the experiment, the value $\bar{\beta}$ was obtained by dividing the total twisted angle by the pushed length of the sheet metal l . In the analysis, the sheet metal was twisted symmetrically to the rolling direction, the specific twisted angle β was obtained from y-axis and the coordinates of the two adjacent nodes, as shown in Figure 6. The average specific twisted angle $\bar{\beta}$ was calculated by averaging the specific twisted angle β in the steady-state range. This average specific twisted angle $\bar{\beta}$ was used to compare the experimental and analytical results.

4. Effect of Roller Axial Position on Twisted Angle

4.1. Experiment and Analysis Results

The effect of the axial position δ on the average specific twisted angle was investigated using sheet thickness $t = 2$ mm and roller skew angle $\varphi = 20^\circ$. Firstly, Table 5 shows the analysis results for finding the minimum value of δ where the sheet metal can be twisted without geometric interference. “S” indicates conditions where there is no interference between the roller and the sheet metal and forming is possible in the experiment, and “F” indicates that interference between the roller and the sheet metal occurs and forming is not possible. When δ is too small, the gap between two rollers is too small at the edge, although the gap is equal to the sheet metal thickness in the middle, as shown in Figure 7. As a result, the gap between two rollers at the metal edge is less than the metal thickness

and makes the sheet metal subjected to thickness reduction and sever deformation, causing undesired roller marks or edge waves. When the experiment was conducted at $\delta = 9$ mm, buckling occurred, as shown in Figure 8. As buckling did not occur at $\delta = 10$ mm, the minimum applicable value of δ in the experiment was found to be 10 mm. In addition, the sheet hardly twisted when δ was set to 30 mm or more in the experiment. Based on these results, the experiments and analyses were conducted with values of δ of 10, 15, 20, and 25 mm in the remainder of this paper. The appearance of the rolled sheet metal is shown in Figure 9 and the average specific twisted angle is shown in Table 6. The average specific twisted angle decreased as the axial position δ increased.

Table 5. Interference results of the value of δ ($\varphi = 20^\circ$, $t = 2$ mm). F: interfered, S: not interfered.

δ/mm	7	8	9	10
Interfere	F	F	S	S

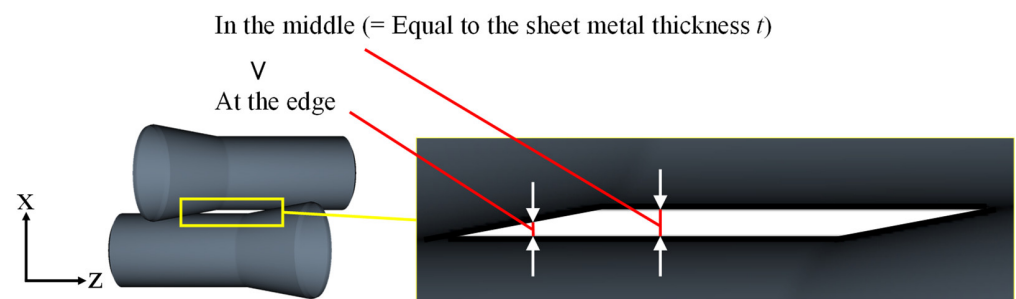


Figure 7. Gap between rollers.

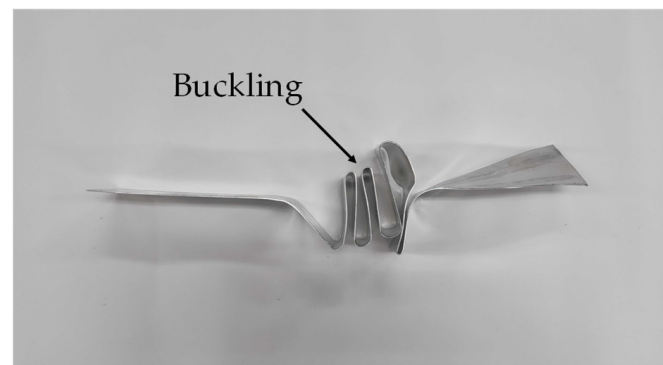


Figure 8. Buckling of formed product in the experiment ($\delta = 9$ mm).

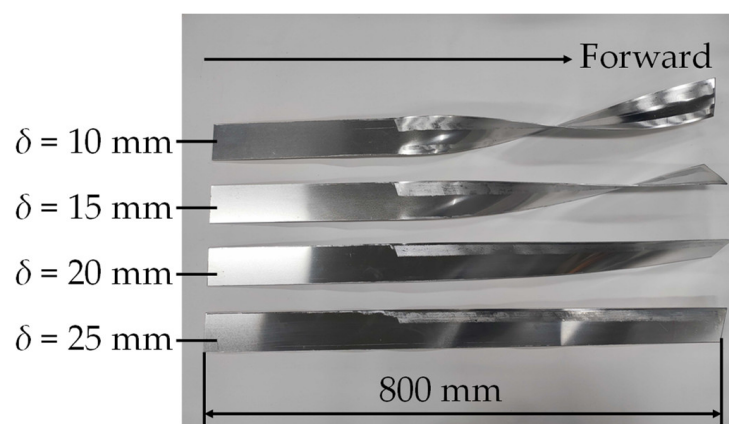


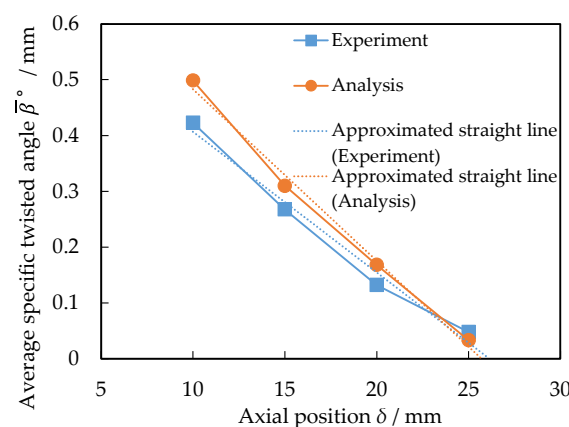
Figure 9. Effect of roll axial position on appearance of the rolled sheet metal.

Table 6. Average specific twisted angle $\bar{\beta}$ ($\varphi = 20^\circ$, $t = 2$ mm). Unit: $^\circ/\text{mm}$.

Roll Axial Position δ/mm	10	15	20	25
Experiment	0.423	0.268	0.132	0.048
Analysis	0.499	0.310	0.168	0.033

4.2. Comparison and Discussion of Results

The experimental results show that the average specific twisted angle decreased as the axial position value increased. Figure 10 shows the effect of the axial position of rollers δ on the average specific twisted angle. The experimental and analytical trends were consistent. Extending the approximate straight line of the graph, the average specific twisted angle became zero at about 26 mm. This suggests that the roll axial position needed to be 26 mm or less to twist the sheet metal. Figure 11 shows the contact surface pressure at axial positions of $\delta = 10$ mm and 25 mm. The contact area was smaller at $\delta = 25$ mm than that at 10 mm. Focusing on the contact point circled in red between the taper section of the roller and the sheet metal, the contact point moved to the right side as the axial position increased. A schematic diagram of moving the axial position from $\delta = 10$ mm to 25 mm is shown in Figure 12. It can be seen that as the axial position increased, the contact point at $\delta = 10$ mm moved downward at 25 mm. In other words, the point of contact with the sheet metal was lowered, which is thought to result in a smaller twisted angle when the axial position increased. For these reasons, it is considered that the specific twisted angle decreased as the axial position increased. Figure 13 shows the distribution of the specific twisted angle along the rolling direction in the analysis at the time when the analysis was completed. At the axial position $\delta = 10$ mm, the graph appears to be wavy. In a previous study [11], a small value for the axial position caused a large pressure hill on the edge of the sheet, resulting in a defective rippling phenomenon on the edge of the sheet metal. Considering that the roll gap at the metal edge was less than the thickness when δ was less than 8 mm in the analysis and buckling occurred at 9 mm in the experiment, the gap between the straight and taper sections of the rollers was narrower than the sheet metal thickness at the edge when δ was equal to or less than 10 mm, which resulted in an increase in the processing load. The conditions of $\delta = 10$ mm and 15 mm were not suitable considering the appearance, as large warpage appeared. Finally, it was concluded that $\delta = 20$ mm was the most suitable condition forming in these conditions. Focusing on the contact surface pressure in the roll straight section in Figure 11, it was found to be linear but not continuous. As the loads in the analysis occurred at the nodes, this result is attributed to the fact that there were no nodes on the straight line, even though it was in fact linear. This result suggests that the number of element divisions should be increased not only at the point of contact with the taper section of the roller and the sheet metal, but also at the point of contact with the straight section for obtaining a precise contact area in the finite element method.

**Figure 10.** The effect of axial position on the twisted angle.

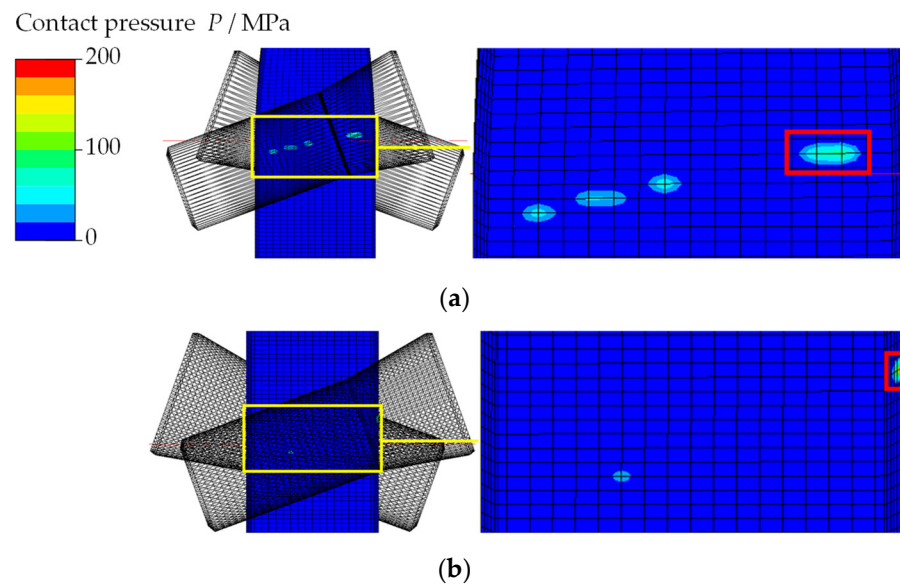


Figure 11. Contact pressure: (a) axial position $\delta = 10$ mm and (b) axial position $\delta = 25$ mm.

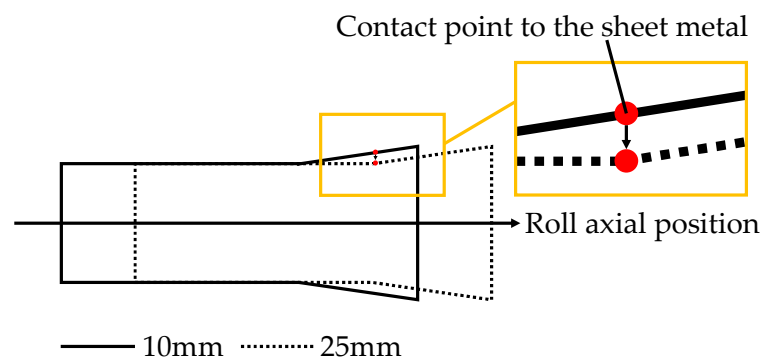


Figure 12. Movement of the contact point to the sheet metal.

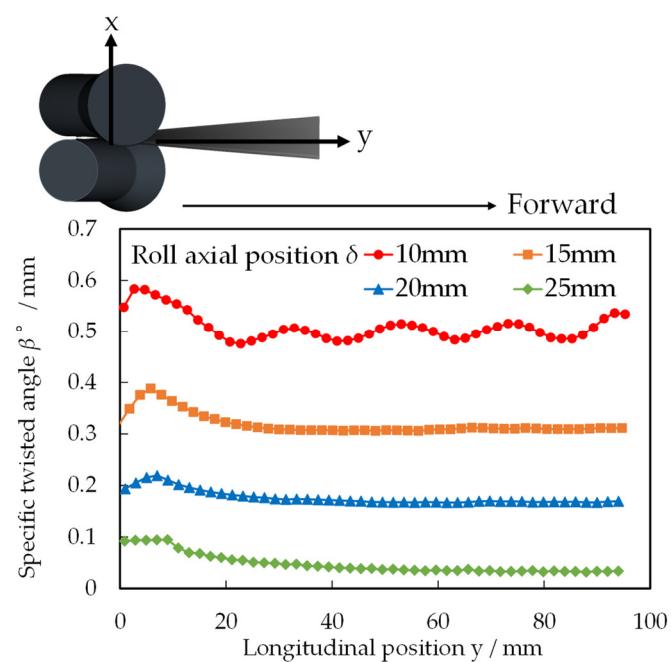


Figure 13. Distribution of the twisted angle along the rolling direction (FEA).

5. Effect of Roller Skew Angle on Twisted Angle

5.1. Experiment and Analysis Results

The effect of the skew angle φ on the average specific twisted angle was investigated under the conditions of sheet metal thickness $t = 2$ mm and roller axial position $\delta = 20$ mm. The skew angles φ were 10° and 20° . The appearance of the rolled sheet metal is shown in Figure 14, and the average specific twisted angle in the experiments and analyses are shown in Table 7. The average twisted angle of the skew angle φ of 10° was larger than that of 20° .

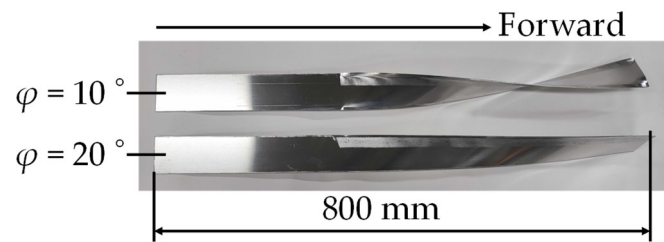


Figure 14. Effect of skew angle on appearance of the rolled sheet metal.

Table 7. Average specific twisted angle $\bar{\beta}$ ($\delta = 20$ mm, $t = 2$ mm). Unit: $^\circ/\text{mm}$.

Skew Angle $\varphi/^\circ$	10	20
Experiment	0.299	0.132
Analysis	0.369	0.168

5.2. Comparison and Discussion of Results

The trends for the experiment and analysis were the same. The twisted angle at $\varphi = 10^\circ$ was larger than that at $\varphi = 20^\circ$. Figure 15 shows contact surface pressure at skew angles $\varphi = 10^\circ$ and 20° . In both conditions, it can be seen that contact occurred at the two locations, which is denoted by A and B. A is in contact with the straight section of the roller and B is in contact with the taper section. The distance (Δl) in the rolling direction between the contact area centers of A and B at skew angle $\varphi = 10^\circ$ was smaller than that at skew angle $\varphi = 20^\circ$. Figure 16 shows a view from the lateral direction. Focusing on the sheet metal thickness direction (x direction), it can be seen that the displacement (Δx) was larger for 10° than for 20° . From these results, it is considered that as the value of the $\Delta x/\Delta l$ increased, the twisted angle increased. For the above reasons, the average twisted angle of the skew angle φ of 10° was larger than that of 20° .

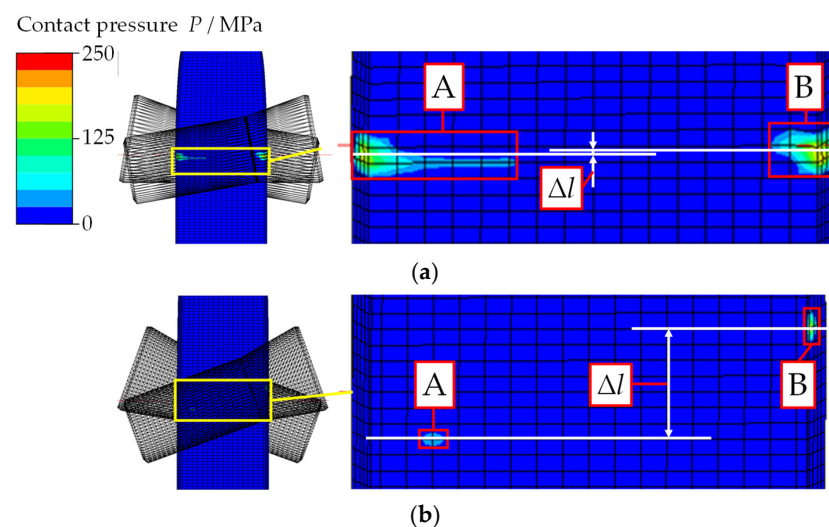


Figure 15. Contact pressure: (a) skew angle $\varphi = 10^\circ$ and (b) skew angle $\varphi = 20^\circ$.

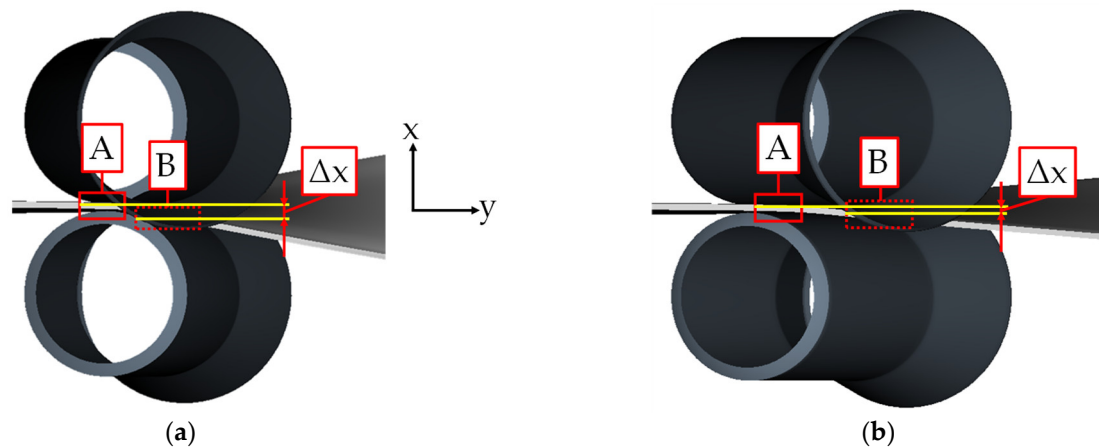


Figure 16. Lateral view: (a) Skew angle $\varphi = 10^\circ$ and (b) Skew angle $\varphi = 20^\circ$.

6. Relationship between Sheet Metal Thickness and Twisted Angle

6.1. Experiment and Analysis Results

The relationship between the thickness of the sheet and the average specific twisted angle was investigated under the conditions of the axial position of the roller $\delta = 20$ mm and skew angle $\varphi = 20^\circ$. The sheet thicknesses t were 1, 2, and 3 mm. The gap between the rollers was set to be equal to the sheet thickness t . The appearance of the rolled sheet metal is shown in Figure 17, and the average specific twisted angle of the experiments and analyses is shown in Table 8. The average specific twisted angle increased as the sheet thickness increased.

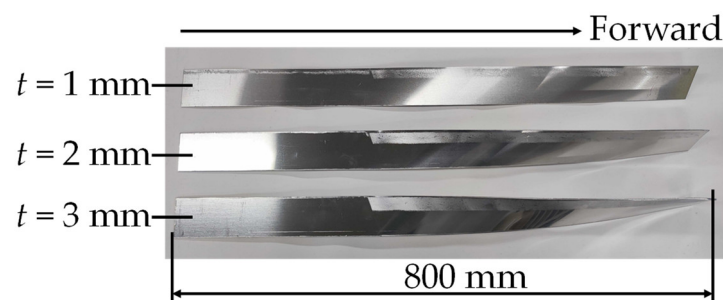


Figure 17. Effect of sheet thickness on appearance of the rolled sheet metal.

Table 8. Average specific twisted angle $\bar{\beta}$ ($\delta = 20$ mm, $\varphi = 20^\circ$). Unit: $^\circ/\text{mm}$.

Sheet Thickness t/mm	1	2	3
Experiment	0.088	0.132	0.158
Analysis	0.122	0.168	0.193

6.2. Comparison and Discussion of Results

The trends for the experiments and analyses were the same. The twisted angle increased with the increase in sheet metal thickness. Figure 18 shows the distribution of the specific twisted angle along the rolling direction in the analysis at the time when the analysis was completed. The values of springback at sheet thicknesses of $t = 1, 2$, and 3 mm are shown as $\Delta\beta_1$, $\Delta\beta_2$, and $\Delta\beta_3$ in Table 9. These results show that the maximum value of the specific twisted angle was almost the same for each sheet thickness condition, but the springback amount was the largest for 1 mm and the smallest for 3 mm. For the above reasons, the average specific twisted angle was considered to have increased as the sheet thickness increased. The skew angle and axial position of the rollers need to be determined considering springback, which is large for thin sheet metals.

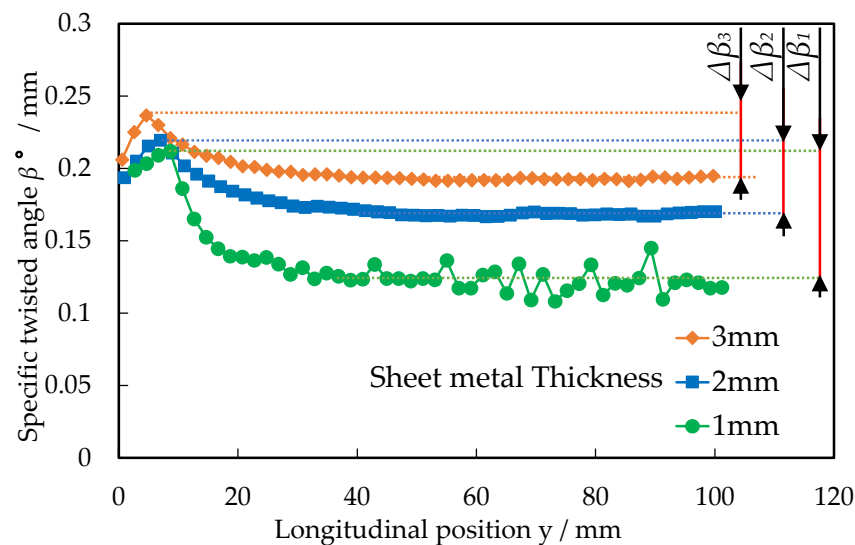


Figure 18. Distribution of twisted angle along the rolling direction (FEA).

Table 9. Springback amount. Unit: mm.

Sheet Thickness t/mm	1	2	3
Springback amount $\Delta\beta_x/\text{mm}$	9.02×10^{-2}	5.11×10^{-2}	4.40×10^{-2}

7. Surface Roughness and Application to Products

7.1. Evaluation of Surface Roughness

The results of surface roughness after forming were measured as shown Table 10. Measurements were taken at a sheet metal thickness of 2 mm, skew angle of 20° , and axial position of 10 mm, which was largest twisted condition. The surface roughness was measured in the rolling direction at the contact points of the sheet metal to the taper and straight sections. It can be seen that the surface roughness after forming increased compared with that before. The taper section of the roller had a higher contact pressure than the parallel section, which suggests that the taper section had a greater forming force than that the straight section. This result could also be confirmed from the results of the contact surface pressure in the analysis. In twist forging [3], in the previous study, steps of 2.3 mm to 4.5 mm were generated on the surface. In this study, the process by rolling was used to form a continuous twisted shape without generating the steps. This indicates that the forming process in this study was superior to the forging processes not only in terms of forming efficiency and yield improvement, but also surface properties.

Table 10. Surface roughness ($t = 2 \text{ mm}$, $\varphi = 20^\circ$, $\delta = 10 \text{ mm}$).

	Before Rolling	After Rolling (Straight Section)	After Rolling (Taper Section)
Arithmetic mean roughness $R_a/\mu\text{m}$	0.203	1.83	1.83
Maximum height roughness $R_z/\mu\text{m}$	1.12	9.53	13.2

7.2. Application to Products

The formed products in this study can be used as industrial components depending on the required specifications, such as agitator parts, propellers, and turbine blades, by changing the forming parameters during forming or adding machining processes. For example, for stirring parts, where a single twisted angle is required without the need for

additional machining, the present process showed that forming with specific twisted angles of $0.048^\circ/\text{mm}$ to $0.423^\circ/\text{mm}$ is possible in this paper. Therefore, it is considered that this formed product could be used as an agitator product as it is. In the case of propellers used for solar power generation and ship propulsion, the specific twisted angle and cross-sectional shape must be changed in the longitudinal direction. The specific twisted angle is considered to be changeable by changing the roller axial position and skew angle during forming. This method is considered near-net-shape processing, the longitudinal cross-sectional shape will be machined, and additional grinding will be required in order to finish the surface properties. The turbine blades are made of a titanium alloy. In this case, hot rolling is considered effective because cold rolling is difficult to form. Hot rolling is possible for heating metal materials by incorporating the induction heating (IH) mechanism into the experimental apparatus or irradiating by laser.

8. Conclusions

The following conclusions can be drawn from the present research:

1. A new processing method called “twist rolling” was developed to form continuously twisted shapes by rolling with taper rollers.
2. The twisted angle increased as the roll axial position decreased, but if it was too small, large warpage appeared.
3. The skew angle of 10° increased the twisted angle more than that of the 20° angle. This could be explained by the ratio of the distance in the height and rolling direction between the contact points at the taper and straight sections of the roller.
4. The average twist angle decreased with the decrease in thickness as the springback was large for the thin sheet metals.
5. The axial position of the rollers and the skew angle needed to be adjusted depending on the sheet metal thickness considering springback.

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