Formability in synchronous multipass spinning using simple pass set

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ABSTRACT

This study is an investigation into the effect of the different parameters of the pass set on the formability in synchronous multipass spinning. Synchronous multipass spinning is a metal spinning method that can produce a noncircular cylindrical shape with a noncircular bottom and vertical walls from a metal sheet. The radial position of the roller tool is synchronized with the spindle rotation while the work piece is formed from a flat disk into the shape of the mandrel step by step along varying trajectories. The tool trajectory is calculated by linear interpolation between the mandrel shape and the blank disk shape along a pass set. Here, a pass is the tool trajectory in the normalized two-dimensional space defined by the radial and axial directions of the mandrel. The aim of this study is to examine the effect of different parameters of the pass set on the formability of two sample shapes, a circular cup and a rectangular box.

The formability was experimentally examined using a rotational pass set and a translational pass set as simple tool trajectories. The rotational pass set consists of curved passes with the same start point and a constantly increasing angle inclination. The translational pass set consists of passes with the same inclination and a start point that is moved by a constant amount. The angle of growth of the rotational pass set, the incremental movement of the translational pass set, and the nominal product height are varied for comparison in the experiments.

Keywords: metal spinning, asymmetric shape, tool trajectory, forming limit, aluminum sheet.

1. Introduction

Metal spinning is a plastic forming method for shapes with rotational symmetry (Music et al., 2010). Since only one male mandrel is used, this method is suitable for high-mix low-volume production where a large variety of products are manufactured in small lots. In previous studies, spinning methods for asymmetric shapes were developed by controlling the roller position while rotating the mandrel.

However, it was not possible to form shapes such as rectangular boxes. Thus, synchronous multipass spinning was developed (Sugita and Arai, 2010). This method enables the formation of rectangular boxes and cups with re-entrant contours in addition to usual asymmetric shapes, including eccentric or oblique shapes.

The tool trajectory in synchronous multipass spinning is calculated from three elements: the mandrel shape, blank shape, and pass set. The pass set corresponds to the tool trajectory in conventional spinning and is described in the normalized two-dimensional space defined by the radial and axial directions of the mandrel. Since the design of the pass set has been dependent on the programmer's experience with the spinning process, forming experiments are required until a formable pass set is discovered.

Therefore, this study is an investigation into the forming limits of synchronous multipass spinning referring to experiments on the formation of cylindrical and rectangular box shapes using pass sets determined from various parameters.

2. Metal spinning

2.1. Classification of metal spinning using a sheet metal blank

Spinning methods for metal sheets are broadly of two types: multipass conventional spinning and shear spinning (Fig. 1). In multipass conventional spinning, a sheet blank is formed into the desired shape using a roller that moves back and forth between the surface of the mandrel and the edge of the blank. The shape of the blank gradually changes from a planar disk to the desired shape. Artisans of metal spinning by hand have long used this method. Although conventional spinning generally requires multiple passes, simple conventional spinning uses only a single pass to form a relatively shallow shape. On the other hand, in shear spinning, a sheet blank is deformed in a single pass along the mandrel. The diameter of the flange is constant during this process. The wall thickness of the product can be estimated using the sine law given by Eq. (1), where t is the wall thickness of the product, t_0 is the thickness of the sheet blank, and α is the angle of the mandrel.

$$t = t_0 \sin(\alpha) \tag{1}$$

Thus, a cylindrical shape cannot be formed by shear spinning since t becomes zero and the wall breaks.

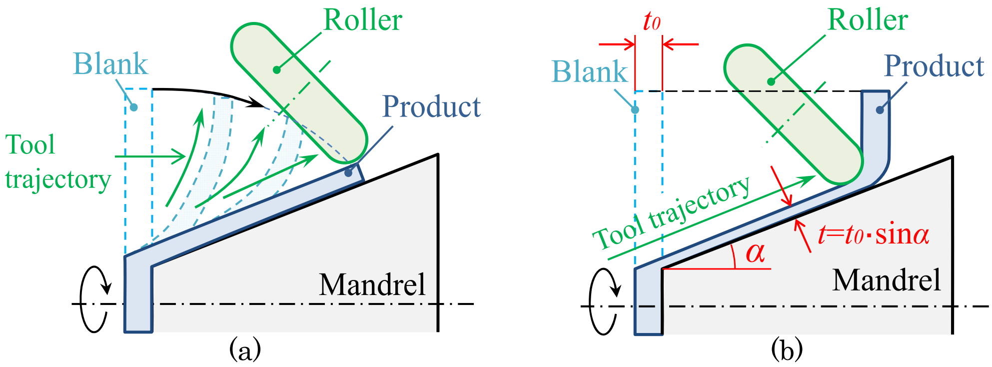

Fig. 1. (a) Multipass conventional spinning and (b) shear spinning.

2.2. Previous studies on asymmetric spinning

In recent years, motion control technology has been applied to metal spinning to form asymmetric shapes.

1) Synchronous spinning

In synchronous spinning, the roller is synchronized with the rotation of the mandrel to follow an asymmetric cross-sectional shape. Amano and Tamura (1984) used a mechanical cam and Arai et al. (2005) used position control to realize this process.

2) Force-controlled spinning

In force-controlled spinning, the pushing force of the roller is controlled in the radial direction of the mandrel while the roller is moved in the axial direction of the mandrel. Therefore, the roller moves along the surface of the mandrel to realize shear spinning. Awiszus and Meyer (2005) used springs and Arai (2005) used force feedback control to apply the pushing force.

3) Synchronous spinning using preformed hollow part

A tripod shape was formed by synchronous spinning from a preformed cone shape by Härtel and Awiszus (2010). They showed that it is possible to form a deep tripod shape with a large deformation volume by a simple pass by using a preformed blank. The trajectory was that of only a single pass. It was demonstrated that the use of the preformed blank enabled large deformation by a single pass. Although this method can be used to form a vertical wall, the bottom shape is limited to a circle.

3. Synchronous multipass spinning

3.1. Purpose of synchronous multipass spinning

A shape with vertical walls and a noncircular bottom is not formable by the methods proposed in previous studies. Thus, a spinning method that meets the following requirements was developed.

1) It can form asymmetric shapes.

2) It can form shapes with vertical walls and a noncircular bottom.

3) The tool trajectory can be easily changed.

To satisfy requirement 2, multipass spinning was adopted. Requirement 3 is necessary because the tool trajectory significantly affects the formability and quality of the product in this method.

3.2. Outline of calculation of tool trajectory

The tool trajectory in synchronous multipass spinning is obtained by linear interpolation of the shapes of the mandrel and the blank disk along a predefined pass set. Here, a "pass" means the trajectory in the normalized two-dimensional plane defined by the radial and axial directions of real space. The coordinates of the pass are used as weight parameters in the interpolation. A "pass set" is the combination of passes used in the entire forming process from the blank to the final shape. The tool trajectory is calculated by the following procedure.

1) The cross-sectional shape of the mandrel is measured at several positions by pushing the force-controlled roller onto the mandrel.

2) The x coordinate corresponding to a point on a pass is calculated. Moreover, the cross-sectional shape at the x coordinate is obtained by interpolating the two neighboring cross-sectional shapes.

3) Next, the y coordinate is calculated by linear interpolation between the blank shape and the cross-sectional shape at the x coordinate calculated in step 2.

4) Steps 2 and 3 are repeated along the pass set to calculate the entire tool trajectory.

The shapes of the mandrel and blank and the pass set are independently treated in this manner. Therefore, each set of data can be separately modified to cope with any changes, for example, if the shape of the mandrel is changed slightly, the same pass set and blank shape can be reused.

3.3. Cross-sectional measurement of mandrel

As shown in Fig. 2, the force of the roller is controlled in the cross-sectional measurement of the mandrel. The position of the roller is kept at the same point in the axial direction of the mandrel while the pushing force in the radial direction of the mandrel is maintained at a constant value. Thus, when the mandrel is rotated, the roller tracks the surface of the mandrel. The position data of the roller and the rotational angle of the mandrel are used to represent the cross-sectional shape of the mandrel. This method has the merit that a complicated geometric model of a nonspherical roller and an asymmetric mandrel are unnecessary.

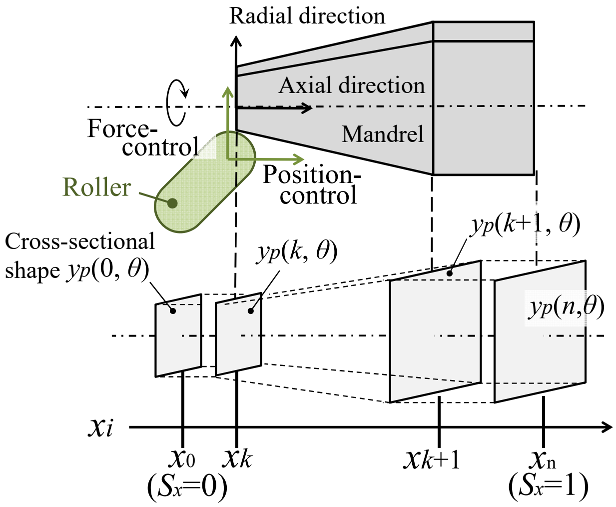

Fig. 2. Cross-sectional measurement of mandrel.

3.4. Pass parts of the pass set

A pass set is a combination of curved and force controlled passes. As shown in Fig. 3, a curved pass is part of an ellipse between the start point and the end point.
In conventional hand spinning, the artisan gradually fits the blank onto the mandrel by moving the roller. In the vicinity of the mandrel, the roller moves almost tangentially to the mandrel surface, and as the roller approaches this curve, Eq. (2) describes a forward pass and Eq. (3) describes a backward pass. The parameter t represents the progress of the pass, which ranges from 0 to 1, where t=0 at the start point and t=1 at the end point. α=π/12 and β= 5π/12.

$$\begin{cases} s_x(t) = q_{xs} + (q_{xe} - q_{xs}) \dfrac{\cos\alpha - \cos((\beta-\alpha)t+\alpha)}{\cos\alpha - \cos\beta} \\ s_y(t) = q_{ys} + (q_{ye} - q_{ys}) \dfrac{\sin((\beta-\alpha)t+\alpha) - \sin\alpha}{\sin\beta - \sin\alpha} \end{cases} \quad (2)$$

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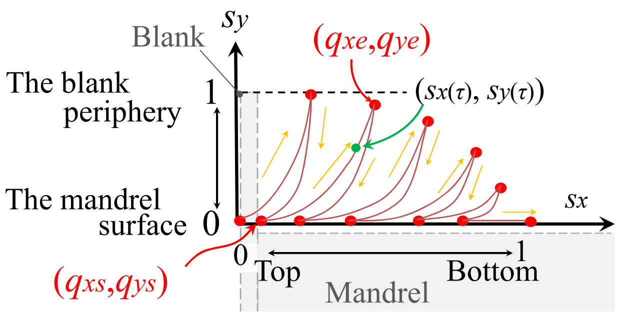

Fig. 3. Curved pass.

A force-controlled pass is a pass in which the force applied by the roller in the radial direction of the mandrel is regulated while the roller position in the axial direction of the mandrel is simultaneously controlled. The parameters of the pass are the pass type, end point (q_{xe}, q_{ye}), feed rate, and spindle speed. In a force-controlled pass, the target force is given instead of q_{ye}. These passes are arranged so as to achieve forming without wrinkles or fractures. S_x and S_y are dimensionless quantities. The roller reaches the blank for the first time when $S_x = 1$. When $S_y = 0$, the roller is on the surface of the product, and when $S_y = 1$ the roller is at the periphery of the blank.

3.5. Calculation of tool trajectory by linear interpolation

The tool trajectory is calculated using the pass set and the cross-sectional shapes of the mandrel as follows (Fig. 4)

1) The tool position x_τ in the axial direction of the mandrel is obtained from S_x using Eq. (4). Then, the interpolation coefficient S_k between the cross sections is calculated from x_τ and the positions of the measured cross section, x_k and x_{k+1}, using Eq. (5).

$$x_\tau = x_0 + (x_n - x_0) \cdot S_x(\tau) \tag{4}$$

$$S_k = \frac{x_\tau - x_k}{x_{k+1} - x_k} \tag{5}$$

2) To calculate the tool position y in the radial direction at x_τ, the cross section at x_τ is calculated by linear interpolation using Eq. (6) between the front cross section (y_k, θ_p) and the back cross section (y_{k+1}, θ_p).

$$y_p(x_\tau,\theta) = S_k y_p(x_{k+1},\theta) + (1 - S_k) \cdot y_p(x_k,\theta) \tag{6}$$

3) y_τ is calculated by linear interpolation between the cross section $y_p(k, \theta)$ and the blank periphery $y_b(\theta)$.

$$y_\tau = S_y(\tau) y_b(\theta) + (1 - S_y(\tau)) \cdot y_p(x_\tau,\theta) \tag{7}$$

4) The tool trajectory is calculated by repeating (1) to (3) along the pass set.

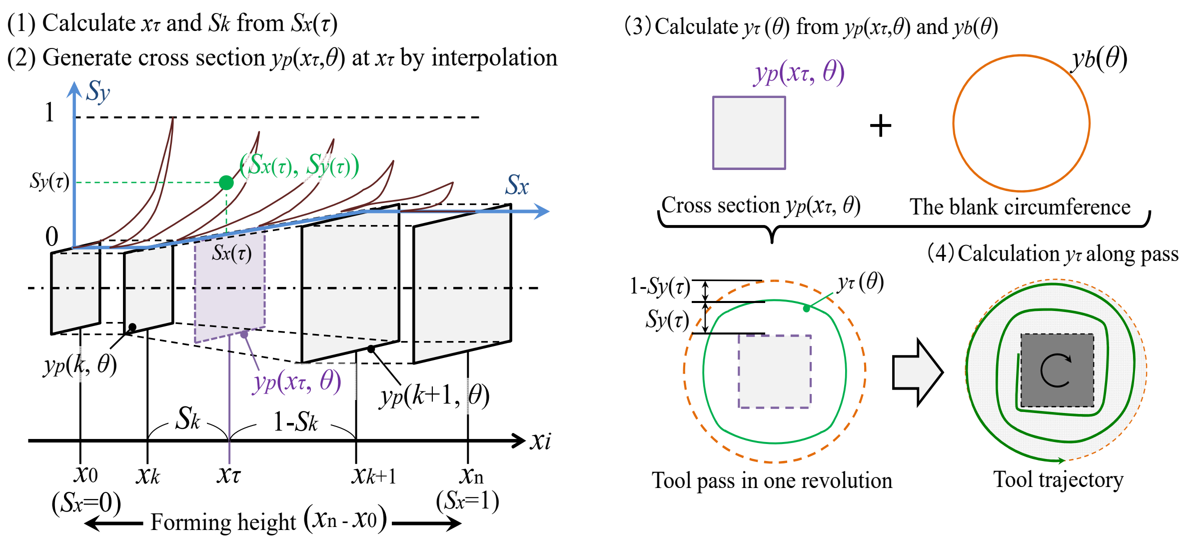

Fig. 4. Calculation of tool trajectory in synchronous multipass spinning.

4. Method of calculating pass set

4.1. Combining passes

The tool trajectory has been conventionally determined through the experience and intuition of artisans, which necessitates some forming trials when a shape is formed for the first time.

Predicting how the blank will deform is more difficult in the forming of asymmetric shapes than in the forming of circular shapes, and hence, it is difficult to determine a formable pass set. Therefore, the formability of the following pass sets (Fig. 5) was examined by carrying out forming experiments with referring Hayama's research (1970).

1) Rotational pass set

2) Translational pass set

Additionally, the formability was classified into wrinkle, fracture, and success in Hayama's research. Therefore in the current study, the formability is defined in the same way.

In the rotational pass set, the pass rotates around the same start point. This pass set is composed of passes in which the angle of the end point relative to the start point is decreased by $\Delta\theta$. The position of the start point does not change.

In the translational pass set, the pass shifts without changing its direction. This pass set is composed of passes in which the angle remains at its initial value θ_0 and the start point moves by $\Delta\alpha$.

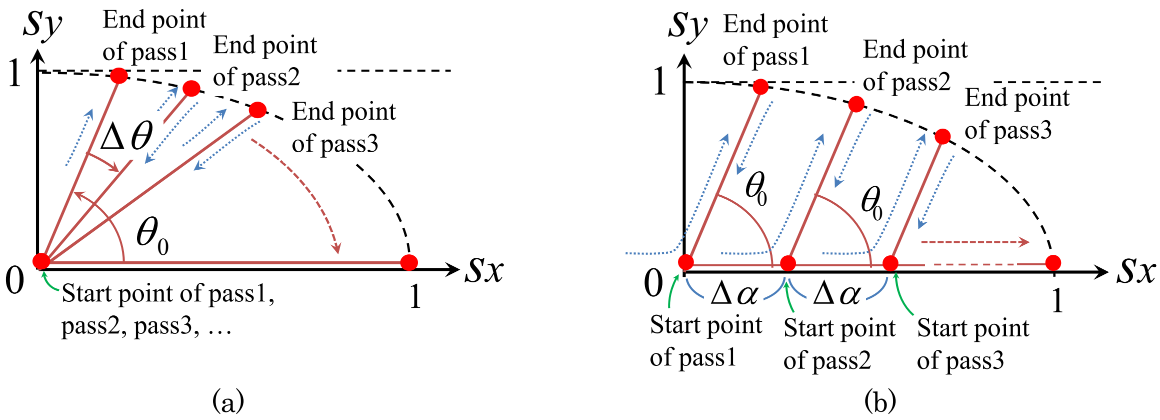

Fig. 5. (a) Rotational pass set and (b) translational pass set.

4.2. Calculation of outer circumference points of passes

The outer circumference point of each pass was calculated to define the pass set. The outer circumference of the blank before forming is represented as (S_x, S_y) = (0, 1) and the end point of the forming process is represented as (S_x, S_y) = (1, 0). However, it is difficult to exactly predict the locus of the outer circumference of the blank during the forming process because it depends on the shapes of the mandrel and the blank, and the pass set. Therefore, the authors here intuitively assumed that the locus can be approximated as a circular arc (Fig. 6).

A straight line that passes through the point (a, 0) with angle θ to the arc is drawn. The point of intersection of the straight line and the arc is defined as the end point of the pass.

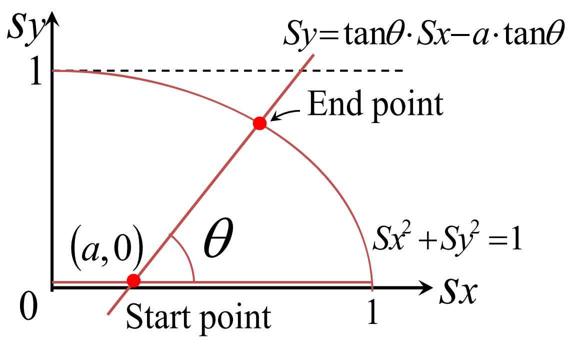

Fig. 6. Calculation of end point of passes.

5. Experimental setup

5.1. Spinning machine and roller

Fig. 7 shows the experimental setup and Table 1 shows the specifications of the spinning machine. The roller is moved by an XY table driven by 400 W AC servomotors and 5-mm-pitch ball screws. The spindle motor is a 400 W AC servomotor with a planetary gearbox having a reduction ratio of 21. A rotary encoder is built into each motor and is used to measure each displacement. A six-axis force sensor is installed at the base of the roller holder. The direction of the roller is arranged to be inclined at 45 deg to the spindle axis. Signals from the rotary encoders and the force sensor are input to a personal computer (CPU: Pentium II, 450 MHz) via I/O boards. The trajectory of the roller is generated and position and force control are implemented using the computer. The current command from the computer for the servomotor is sent to the motor drivers via a D/A board. The sampling period is 1 kHz.

The roller has a diameter of 70 mm and a corner of 8 mm and is made from AISI D2 tool steel. Tissue paper is used to wipe the roller to remove the material exfoliated during forming.

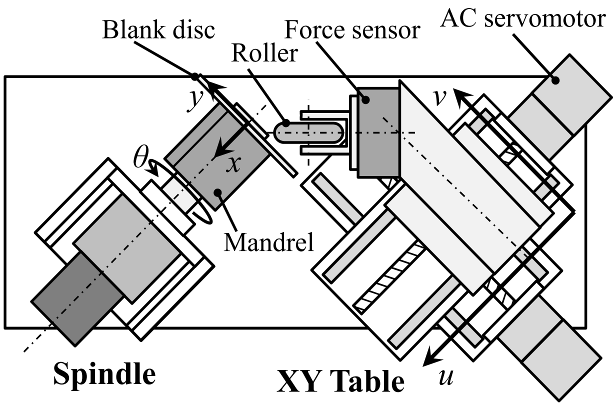

Fig. 7. Spinning machine used in the experiment.

Table 1 Specifications of the spinning machine.

	u, v-axis	θ-axis
Rated force/torque	800 N	13.4 N/m
Rated speed	0.25 m/s	142.min^{-1}
Active stroke	0.15 m	-

5.2. Mandrel and blank used to form circular cup shapes

Mandrels with a cylindrical shape and a prismatic shape were used in the forming experiments. The purpose of the experiments with the cylindrical mandrel is to confirm the effectiveness of the proposed algorithm. In addition, the effects of each pass set on the formability and the wall thickness will later be compared with those in the case of a rectangular box shape. The mandrel used in experiments on the forming of circular cup shape was cylindrical and had a circular base with a diameter of 85 mm and a height of 90 mm (Fig. 8). The mandrel was made of AISI1045 carbon steel and its corners were rounded to a radius of R2.

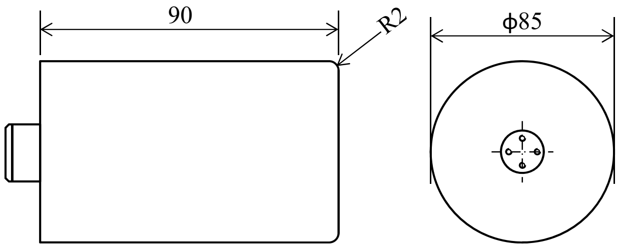

Fig. 8. Cylindrical mandrel used to form circular cup shapes.

The blank used in the experiments was a circular disk of 1 mm thickness and 150 mm diameter. The blank was made of pure aluminum (1100-H24). The equivalent drawing ratio, Z, which is the ratio of the diameter of the blank, *D*, to the diameter of the mandrel, *d,* was 1.76 Eq. (8).

$$Z = D / d \tag{8}$$

5.3. Mandrel and blank used to form rectangular box shapes

The mandrel used in experiments on the forming of rectangular box shapes was prismatic and had a square base with dimensions of 60 x 60 mm and a height of 90 mm (Fig. 9).

The mandrel was made of AISI1045 carbon steel and its corners were rounded to a radius of R1. The blank used in the experiments was a circular disk of 1 mm thickness and 120 mm diameter. The blank was made of pure aluminum (A1100-H24). The equivalent drawing ratio was 1.41 in the diagonal direction and 2.00 in the normal direction to the edge.

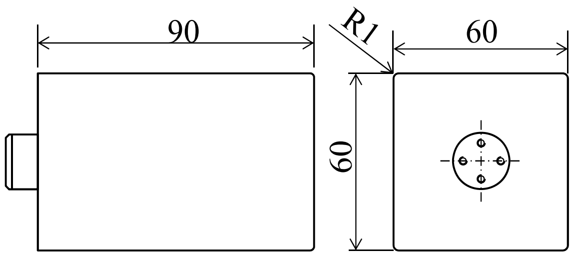

Fig. 9. Prismatic mandrel used to form rectangular box shapes.

6. Forming experiments

6.1. Common settings

Forming experiments was carried out to determine the formability for various rotational pass sets and translational pass sets using the spinning machine, the mandrels, and the blanks described in the previous section.

The pass sets were composed of curved passes and force-controlled passes. To fit the material onto the mandrel tightly, a force-controlled pass was added at the end of each pass set. The spindle speed was 30 rpm and the pitch of the roller, i.e., the roller feed per spindle rotation, was 1 mm/rev in each experiment. However, the spindle speed of the force-controlled passes was 15 rpm for the rectangular box shape since there was contact between the mandrel and the roller. In the force-controlled passes, the desired value of the pushing force was 500 N.

6.2. Circular cup shapes and rotational pass sets

The experiments on the forming of circular cup shapes using the rotational pass sets were carried out with the parameters given in Table 2. Here, the "forming height" is the distance between the first and the last cross section in Fig. 4. It is $x_n - x_0$ in Eq. (4). The position of the last cross section x_n is adjusted to change the forming height.

Table 2 Parameters of rotational pass sets used in forming of circular cup shapes.

Initial position	-0.01
Initial angle [deg]	80
Angle of growth [deg]	6, 8, 10, 12
Forming height [mm]	45, 50, 55, 60, 65

An example of the formed products is shown in Fig. 10. Fig. 11 shows plots of the formability, which indicate whether or not the forming was successful, and if not, how it failed. When the forming height was set to less than 60 mm, forming was possible up to an angle of growth of 10 deg. When the forming height was set to 60 mm or above, the maximum angle of growth was 8 deg.

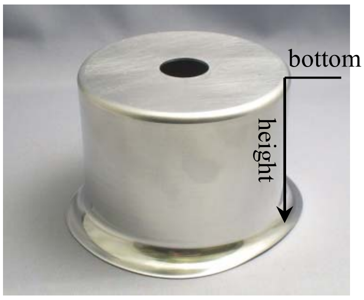

Fig. 10. Example of circular cup shapes formed using rotational pass set. The angle of growth was 10 deg and the forming height was 55 mm.

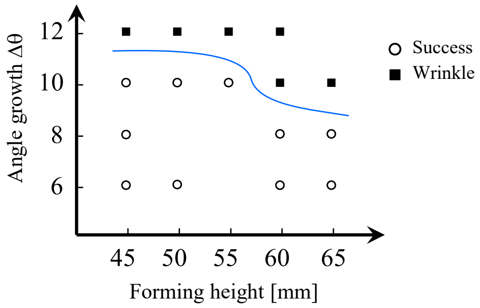

Fig. 11. Plots of the formability of circular cup shapes using rotational pass set.

The wall thickness distributions were measured with a micrometer. Fig. 12 shows the wall thickness distribution of the product when the angle of growth was 10 deg. The graph has a bathtub shape. The thickness is not affected by the forming height near the open side.

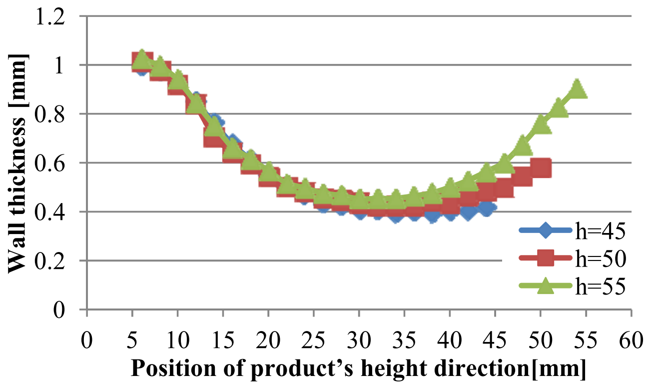

Fig. 12. Wall thickness distributions of circular cup shapes formed using rotational pass sets with angle of growth of 10 deg.

6.3. Circular cup shapes and translational pass sets

The experiments on the forming of circular cup shapes using the translational pass sets were carried out with the parameters given in Table 3.

Table 3 Parameters of translational pass sets used in forming of circular cup shapes.

Initial position	-0.01
Initial angle [deg]	80, 62
Incremental movement	0.06, 0.08, 0.10, 0.12, 0.15
Forming height [mm]	45, 50, 55, 60

An example of a formed product is shown in Fig. 13, and plots of the formability are shown in Fig. 14. For the pass set with the initial angle of 80 deg, the forming was unsuccessful since fracture always occurred regardless of the incremental movement for forming heights of 45 mm and 60 mm. Therefore, the initial angle was changed to 62 deg and carried out the forming experiments again. For this initial angle, this experiment yields that it was possible to increase the incremental movement by increasing the forming height.

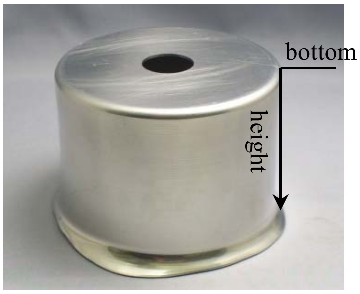

Fig. 13. Example of circular cup shapes formed using translational pass set. The incremental movement was 0.10 and the forming height was 55 mm.

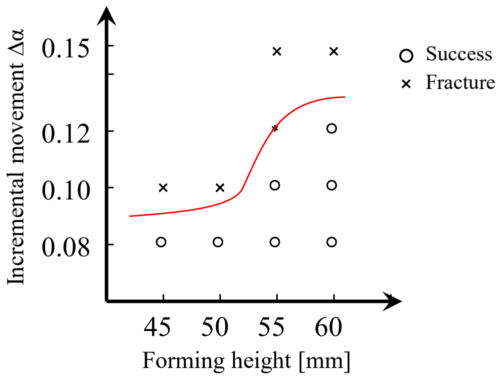

Fig. 14. Plots of the formability of circular cup shapes using translational pass set.

Fig. 15 shows the wall thickness distribution of a product formed with a pass set with an incremental movement of 0.1. The graph has the shape of a bathtub and the minimum thickness is 0.4 mm. The thickness is not affected by the forming height near the open side, similarly to the case of the rotational pass sets. Fig. 16 shows the wall thickness distribution of a product for which the forming height was set to 60 mm. In Fig. 16, there is a fracture at the point where the line is interrupted. This figure shows that as the incremental movement increased, the flange expanded and the thickness near the open side decreased.

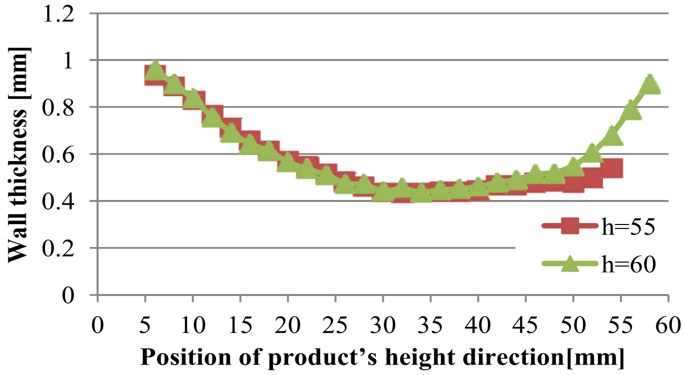

Fig. 15. Wall thickness distributions of circular cup shapes formed using translational pass sets with incremental movement of 0.1.

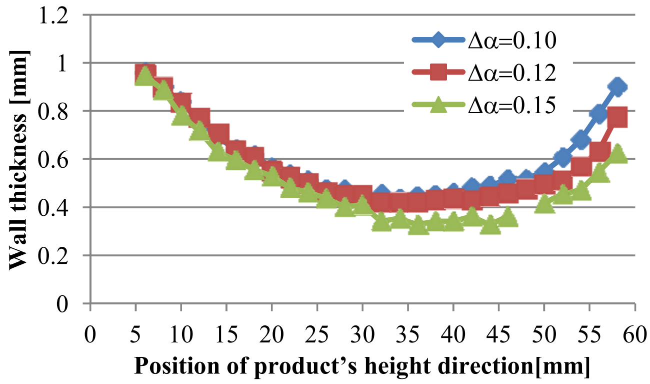

Fig. 16. Wall thickness distributions of circular cup shapes formed using translational pass sets with forming height of 60 mm.

6.4. Rectangular box shapes and rotational pass sets

The experiments on the forming of rectangular box shapes using the rotational pass sets were carried out with the parameters given in Table 4.

Table 4 Parameters of rotational pass sets used in forming of rectangular box shapes.

Initial position	-0.01
Initial angle [deg]	80
Angle of growth [deg]	3, 4, 5, 6
Forming height [mm]	25, 30, 35, 40

An example of a formed product is shown in Fig. 17, and plots of the formability are shown in Fig. 18. Material accumulated at the corner of each product. The maximum product heights were approximately 30 mm regardless of the parameters of the pass set.

When the angle of growth was small, it was possible to successfully form the products. However, forming became more difficult as the angle of growth increased.

Sugita and Arai (2012) examined the wall thickness distribution in the circumferential direction. It was found that the wall thickness was increased at the corner, as shown in Fig. 19. In this study, the wall thickness at the midpoint of the side wall, which is 90 deg in Fig. 19, is measured to compare the wall thickness distribution in the height direction. Fig. 20 shows the wall thickness distribution of the products formed using the pass set with an angle of growth of 3 deg. The wall thickness was nearly constant in the height direction.

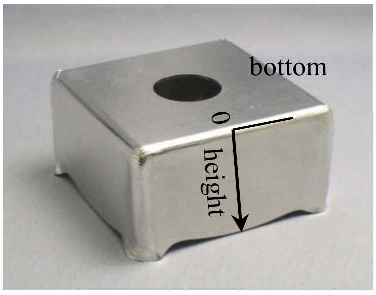

Fig. 17. Example of rectangular box shapes formed using rotational pass set. The angle of growth was 4 deg and the forming height was 30 mm.

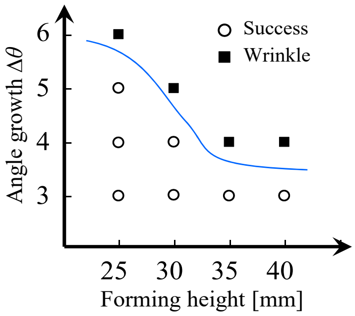

Fig. 18. Plots of the formability of rectangular box shapes formed using rotational pass set.

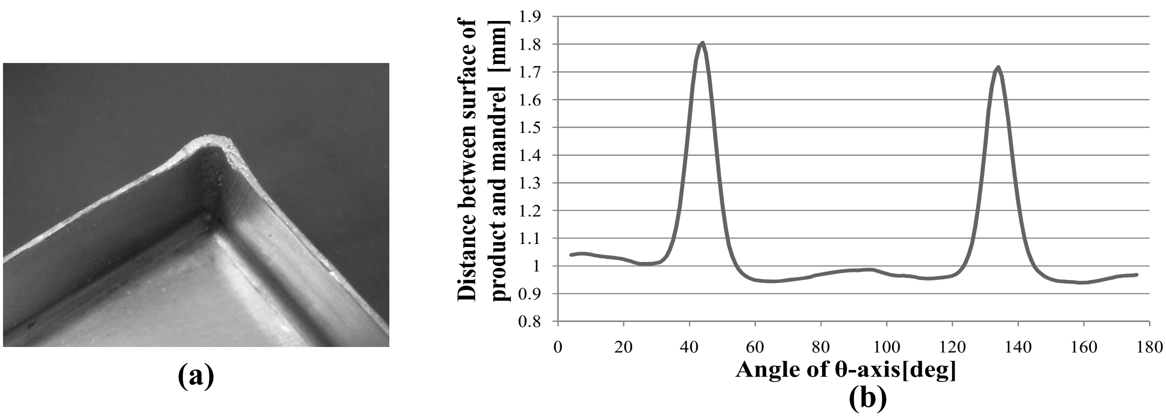

Fig. 19. Increase in wall thickness at the corner. (a) Cross section and (b) distance between surface of product and mandrel Sugita and Arai, 2012.

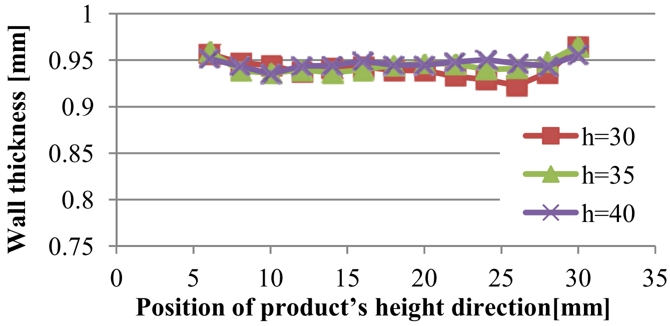

Fig. 20. Wall thickness distributions of rectangular box shapes formed using rotational pass sets with angle of growth of 3 deg.

6.5. Rectangular box shapes and translational pass sets

The experiments on the forming of rectangular box shapes using the translational pass sets were carried out with the parameters given in Table 5.

Table 5 Parameters of translational pass sets used in forming of rectangular box shapes.

Initial position	-0.01
Initial angle [deg]	80, 62
Incremental movement	0.05, 0.06, 0.08, 0.10, 0.12
Forming height [mm]	25, 30, 35, 40

An example of a formed product is shown in Fig. 21, and plots of the formability are shown in Fig. 22. The walls of the products were under much greater strain than those of products formed using the rotational pass sets. Some products have wrinkles in their flange. The incremental movement was maximized by setting the forming height to 35 mm in the experiment when the initial angle was 80 deg. However, the maximum incremental movement was achieved when the forming height was set to 25 mm in the experiment with an initial angle of 62 deg.

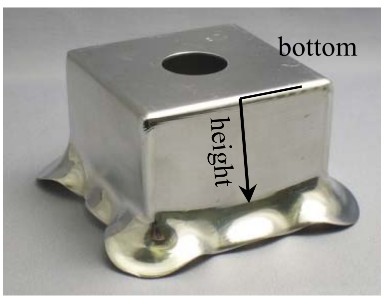

Fig. 21. Example of rectangular box shapes formed using translational pass set. The incremental movement was 0.05 deg and the forming height was 30 mm.

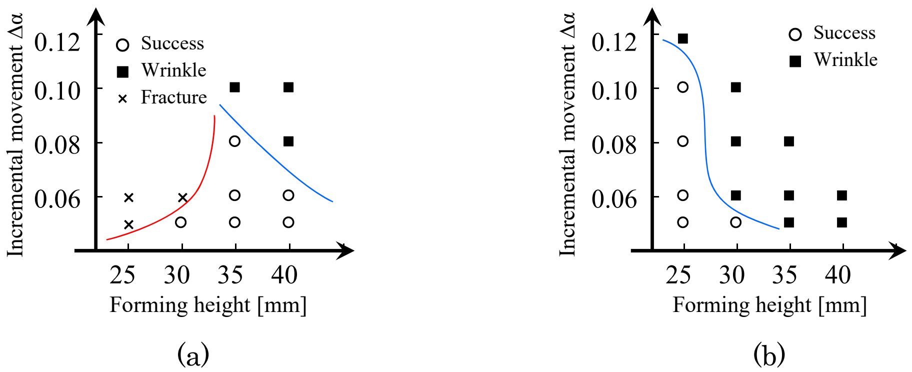

Fig. 22. Plots of the formability of rectangular box shapes formed using translational pass set. (a) Initial angle is 80 deg. (b) Initial angle is 62 deg.

The wall thickness distributions of products formed using translational pass sets with initial angles of 80 deg and 62 deg are respectively shown in Fig. 23 and Fig. 24. Each graph has a bathtub shape. The wall thickness tends to be maintained when the pass set has a sufficiently large forming height. In contrast, the thickness is excessively reduced when the forming height is too small. This is assumed to be because the tool cannot reach the edge of the blank disk at the circumference end of the pass since the tool trajectory is shorter than the flange, and the material expanded in a similar way to that observed in shear spinning.

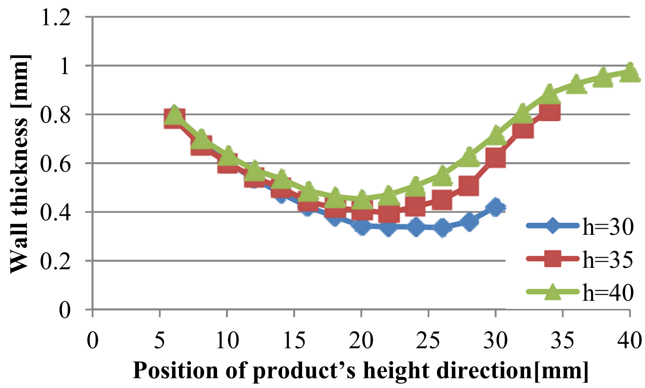

Fig. 23. Wall thickness distributions of rectangular box shapes formed using translational pass sets with initial angle of 80 deg and incremental movement of 0.05.

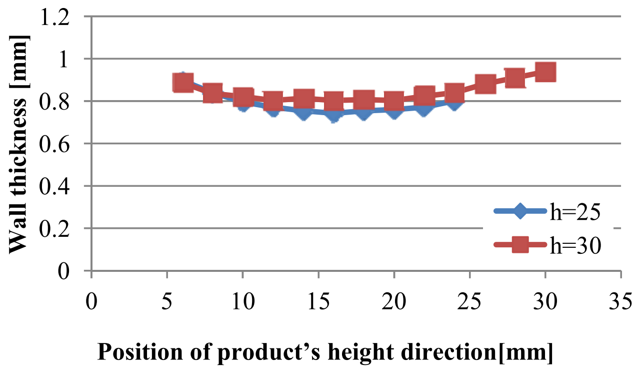

Fig. 24. Wall thickness distributions of rectangular box shapes formed using translational pass sets with initial angle of 62 deg and incremental movement of 0.05.

6.6. Comparison between circular cup shapes and rectangular box shapes

The obtained circular cup shapes and the rectangular box shapes are compared here. With regard to the formability, similar results were obtained with rotational pass sets for both in shapes that an excessive angle of growth led to wrinkles. The rectangular box shapes were more subject to wrinkles than the circular cup shapes and required many passes to obtain successful results.

In the case of the translational pass sets with excessive incremental movement, the types of failure were fractures for the circular cup shapes and mainly wrinkles for the rectangular box shapes. The translational pass sets with a large initial angle were unsuccessful in forming circular cup shapes, although they could form rectangular box shapes.

In the forming of the circular cup shapes, the wall thickness distributions when using the rotational and translational pass sets were both bathtub-shaped. However, in the forming of the rectangular box shapes, different results were obtained: the wall thickness distribution was flat with the rotational pass sets and bathtub-shaped with the translational pass sets. This difference might be due to the blank deformation being similar to bending in the rotational pass set and deep drawing in the translational pass set. Therefore, in the forming of the rectangular box shape, it can be considered that the rotation parameter contributes to the preservation of the wall thickness and the translational parameter results in the reduction of the wall thickness. A summary of the forming result in given in Table 6.

Table 6 Summary of the forming results.

Products shape	Pass set type	Minimum number of passes	Type of failure	Wall thickness distribution
Circular cup	Rotational	9	Wrinkle	Bathtub

	Translational	9	Fracture	Bathtub
Rectangular box	Rotational	21	Wrinkles	Flat
	Translational	14 / 11	Fracture / wrinkles	Bathtub

7. Conclusion

This paper presented the results of forming experiments in which circular cup shapes and rectangular box shapes were formed by synchronous multipass spinning with rotational pass sets or translational pass sets. When rectangular box shapes were formed using rotational pass sets, wrinkles similar to those in the circular cup shapes occurred. In the forming of rectangular box shapes with translational pass sets, wrinkling or fracture was observed for excessive incremental movement. The wall thickness distributions of the rectangular box shapes formed using the rotational pass sets did not decrease markedly from the original thickness, whereas the wall thickness distributions in other cases had a bathtub shape. The reduction of the wall thickness was lessened when the forming height was sufficiently large for both pass sets and both product shapes.

In future research, the forming limits of combinations of rotational pass sets and translational pass sets will be investigated.

Then, it is expected that the automatic calculation algorithm for the pass set is improved with considering the characteristics of the forming limit.

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