# Synchronous Die-less Spinning of Curved Products

**Akio Sekiguchi[1], Hirohiko Arai[2]**

[1] Graduate School of Systems and Information Engineering, University of Tsukuba, Tsukuba / Japan, a.sekiguchi@aist.go.jp; [2] Advanced Manufacturing Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba / Japan

Products formed by metal spinning have been inherently limited to straight, axisymmetric shapes. In order to enhance the application of spinning, this study is aimed at developing a novel sheet spinning method which can form products of curved, non-axisymmetric shape without using a dedicated die. The fundamental strategy of this process is the synchronization of the motion of the roller tool in the axial and radial directions with the rotations of the workpiece on the spindle axis. A numerically controlled spinning machine moves the tool along a trajectory which is calculated based on the desired shape in terms of the contact point with the tool, and the tool velocity relative to the desired surface is maintained constant. Pure aluminum sheets, 150 mm in diameter and 1.5 mm in thickness, were mainly used as blanks in our forming experiments. Curved cones with bends of up to 60 degrees and curved asymmetric shapes, e.g. with cross-sectional changes from a circle to a pentagon, were formed successfully. An equation is proposed to estimate the wall thickness of the product, based on a curved shear deformation model around a flexural center. It was verified that the model coincides nearly with the measured thickness distributions of the products. The proposed method can be applied to the rapid manufacturing of a wide variety of products in small quantities simply by changing the NC code of the tool trajectory.

**Keywords**: Metal spinning, Die-less forming, Curved products, Formability, Numerical control, Tool trajectory, Rapid prototyping

## Introduction

Metal spinning [1] is a rotary incremental forming process which is suited to the trend of manufacturing a wide variety of products in small quantities, e.g. the low-cost production of special-order parts or trial products.

In recent years, the industrial field of spinning has been enhanced to encompass more low-cost and flexible shaping, as a result of studies on novel spinning lathes and the application of intelligent technologies. Dedicated die-less forming methods for shaping sheet metal into conic parts have been proposed by Shima et al. [2] and Kawai et al. [3]. Asymmetric sheet spinning methods have been developed by Amano et al. [4], Gao et al. [5], Awiszus et al. [6] and Arai [7]. Curved shapes can be successfully formed on a novel tube-spinning lathe created by Shindo et al. [8], and incremental sheet forming can be achieved through a method developed by Matsubara [9], which buckles out the intended shape. However, there is as yet no method which brings all of these advantages to metal spinning.

This study is aimed at developing a novel sheet spinning method which can form curved shapes and non-axisymmetric sectional shapes without using a dedicated die. In this method, a numerically controlled spinning lathe is used to force the spherical head tool onto the pre-hemmed blank disc fixed on the spindle axis via a general-purpose mandrel, with the tool moving along a trajectory which is calculated based on the desired shape. The basic specifications, e.g. the profile, wall-thickness distribution and forming limit, are discussed with reference to the results of our forming experiment featuring curved cones and curved asymmetric shapes made from a 1.5-mm-thick pure aluminum blank. A simplified shear deformation model around a flexural center is suggested for the purpose of estimating the wall thickness of the products.

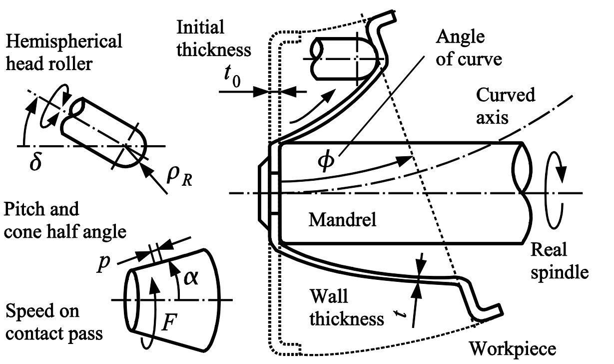


**Figure 1.** Schematic of the synchronous spinning of the curved product.

## Fundamental Strategy

Arai et al. [10] have shaped tube blanks into non-axisymmetric products by moving a roller tool in the radial direction synchronously with the angle of the main spindle. The fundamental strategy in the present study has a similar premise: to move the tool in the axial and radial directions synchronously with the rotation of the spindle axis, and to form the product according to the virtual curved axis instead of the real spindle-axis, as shown in **Figure 1**. Since the flange plane of the workpiece is inclined from the normal plane of the spindle axis, the position of the roller and the angle of the spindle should be controlled synchronously, as illustrated in **Figure 2**.

In this sheet spinning process, the profile of the product is mainly determined along the envelope surface of the helix trajectory of the contact points between the work-

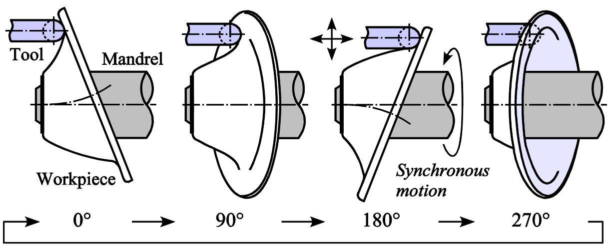


**Figure 2.** Synchronous motion of the tool over the course of one round of the spindle.

piece and the roller tool. In accordance with this method, the tool trajectory data are calculated based on the desired shape in terms of the tight helix trajectory of the contact points along the above virtual curved axis, and are transformed into coordinates of the numerically controlled spinning lathe: the spindle angle, $\theta$, and the movable *r-z* plane of the tool.

In shear spinning, it is known that the wrinkling of the flange of the workpiece can be suppressed by forcing enough of the roller onto the mandrel, but this is not possible in a die-less process. The edge of the blank sheet in the present method is bent in advance, to structurally reinforce the flatness of the flange by enhancing the stiffness against radial tension and circumferential buckling.

### Experimental Setup

**Forming system.** The numerically controlled 5-axis spinning lathe developed in [10] was used to test the method. The roller tool can be moved in synchrony with the angle of the spindle by means of the control panel, while the tool trajectory data are transferred from a personal computer. In this study, the number of data points per one revolution was 60 for circular sectional shapes and 120 for asymmetric shapes. The intervals between the data points were linearly interpolated in the mechanical coordinate system.

**Blank and tools.** **Figure 3a** illustrates a blank disc of pure aluminum (A1050P-H24, nominal thickness of 1 mm), whose edge is hemmed in advance by simple conventional spinning. The blank is formed by fixing two types of mandrel: one has a simple circular head, and the other has a head inclined by 30° toward the spindle axis (Figures 3b and 3c). Before the forming, a general-purpose lubricant, CRC5-56, was sprayed on the blank. Unlike in conventional spinning using a roller, the spherical head tool shown in Figure 1 is used for fine shaping, and the tool

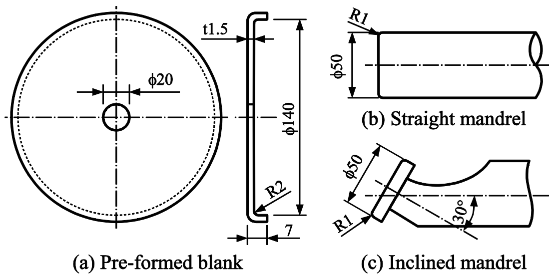


**Figure 3.** Pre-formed blank and straight/inclined mandrel.

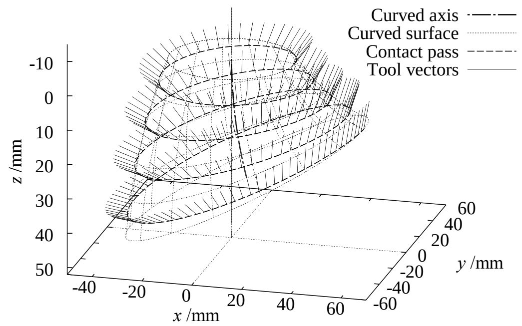


**Figure 4.** Example of a helix tool trajectory along the surface of a curved product.

offset can be easily calculated. The base of the tool is supported to allow free rotation with the bearings.

**Tool pass calculation.** The helix tool trajectory necessary for obtaining the desired profile is geometrically calculated from the point of contact with the tool by a computer in program written in the C language, as exemplified in **Figure 4**. The production time can be calculated simultaneously. The feed rate per revolution along the curved axis, *p*, was set at 0.2 mm in the maximum gradient direction of the desired cone shape. In this experiment, the relative speed of the contact point, *F*, was mainly configured at 8,000 mm/min as the spalling-less condition.

### Forming Experiments

**Forming of curved cone shells.** To evaluate the present method, curved cone shapes, in which the cone axis is curved in an arc at various half-angles, $\alpha$, and bend angles, $\phi$, were formed as shown in **Figure 5**.

The process took about 12 minutes for the shape shown in Figure 5d. The outer surfaces of the products were covered with glossy feed marks of the trajectory of the point of contact with the roller. In contrast, the inner surfaces were rough as compared with the original surface of the blank, since deformations resulted from the successive integration of localized bending along the helix contact pass. In the forming of the shape shown in Figure 5d, the inclined-head mandrel (Figure 3c) was used to prevent interference between the mandrel and the workpiece. Due to this same limitation, the maximum bend angle with the present setup was 60°.

**Profile of the product.** **Figure 6** shows the difference between the outer profile measured by a laser sensor (solid line) and the desired profile used in calculating the tool trajectory (dashed line), at $\alpha$ = 30° and $\phi$ = 20°. The forming time was about 8 minutes. The error of the profile at the base of the cone is suspected to be the cause of the springback. Unlike the known process developed by Matsubara [9], which can shape curved shells from sheet blanks, the present method can form the intended shape approximately along the envelope surface of the tool trajectory.

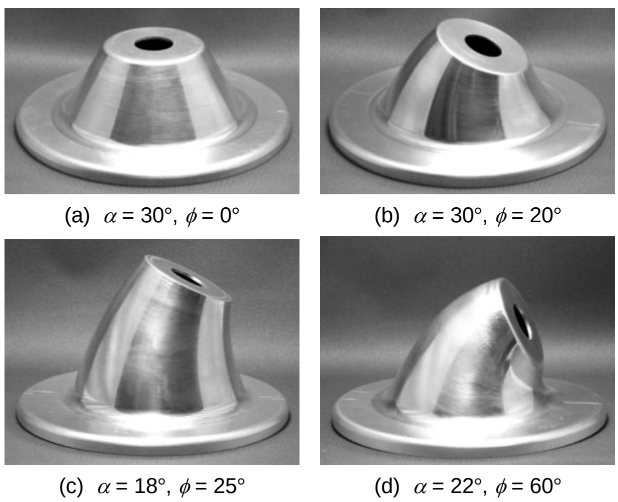


**Figure 5.** Curved cone products.

**Wall-thickness distribution and deformation model.** **Figure 7** shows the wall thickness ratio distribution along the outer/inner side of the product at $\alpha = 30°$ and $\phi = 0°$, 10°, 20° and 35°, arranged according to the non-dimensional distance from the head (= 0) to the base (= 1) of each cone. In the straight shape ($\phi = 0°$), the wall thickness confirms the sine law: $t/t_0 = \sin 30° = 0.5$. In the other cases, the thickness reduction is moderated on the inner wall of the curve and encouraged on the outer wall, and this effect is stronger as the bend angle, $\phi$, increases.

Incidentally, in forming a gridded blank disc, it was observed that its flange plane remained flat with no eccentricity toward the cone, and that no deformation occurred in the radial or circumferential direction. Abstracting from the local deformations at the point of contact with the tool, the behaviour can be simplified as an incrustation of the contour shear deformation along the arc curved axis with a curvature radius of $R_0$ (**Figure 8**). At minute fractions, the wall-thickness ratio, $t/t_0$, can be geometrically calculated using the following equation:

$$\frac{t}{t_0} = \frac{dR}{\sqrt{(Rd\phi)^2 + dR^2}} = \left\{1 + \left(\frac{\eta}{\tan\alpha}\right)^2\right\}^{-1/2} \qquad (1)$$

where $\eta$ is the ratio of the distance from the flexural center to the curvature radius of the curved axis, $R/R_0$. The measured thicknesses and the thickness distribution estimated by means of this equation nearly coincided.

**Forming limit.** **Figure 9** shows the limit of non-fracture forming of curved cones at various bending angles, $\phi$, and cone half-angles, $\alpha$. The fracture condition is indicated by filled marks. At a constant half-angle, the wall thickness decreases at the outer wall of the bend. The upward-sloping curves indicate the estimation of the minimum thickness ratio of the wall, $t/t_0|_{min}$. When forming with a straight mandrel, the limit can be approximated by $t/t_0|_{min} = 0.235$ (thickness strain: $\varepsilon_t|_{min} = 1.45$), while the trend is different with the inclined-head mandrel. In forming conditions exceeding the A-line of the graph, a flexural uplift of the preformed wall is observed, since $\eta$ partly becomes negative and the wall is deformed by the rising flange.

**Forming of products with a non-arc axis.** Inclined-cone products with a profile which connects two different circular sections in a straight line were formed as practical shapes (**Figure 10**). The eccentricity of the flange depends on the positional relationship between the two sections. These results suggest a deformation mode in common with the model shown in Figure 8: the flexural center moves freely during forming.

**Forming of curved asymmetric shells.** **Figure 11** shows curved non-axisymmetric shapes in which the section changes linearly from a circle, 50 mm in diameter, to an $n$-sided rectangle ($n$ = 4, 5, 6) or ellipse (oblateness: $f$ = 0.27), 110 mm in circumcircle diameter. These shapes are formed successfully at a minimum half-angle of $\alpha = 20°$, an arc-curved angle of $\phi = 20°$ and a relative feeding speed of 10,000 mm/min. The production time was 12 minutes for the tallest shape with $n$ = 6. The surface of the outer walls is also glossy, and the corners of the rectangles are rounded to about 3 mm.

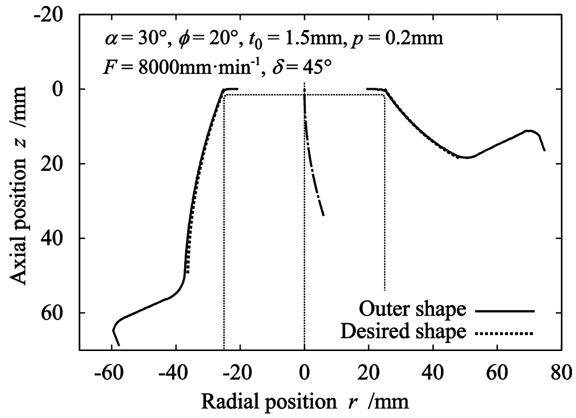


**Figure 6.** Profile of a curved cone product with the desired shape.

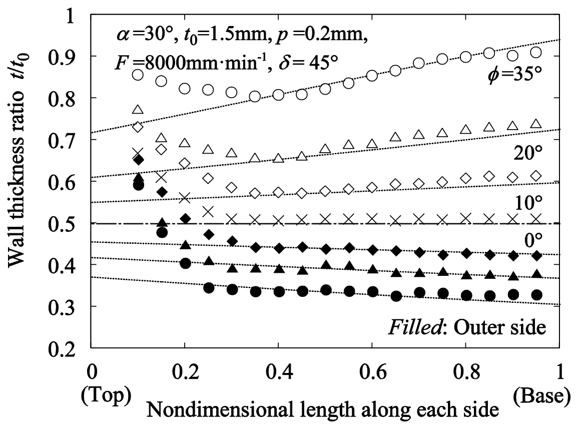


**Figure 7.** Wall thickness ratio distributions along the outer/inner wall of the products at each angle, $\phi$, of the curve, with estimation lines.

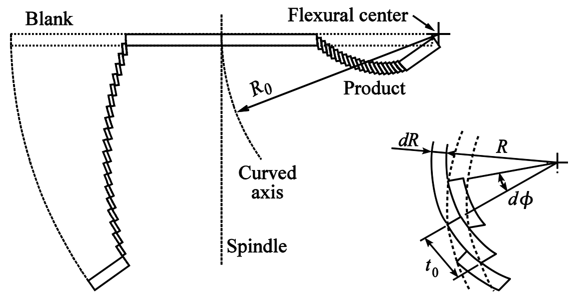


**Figure 8.** Shear deformation model of the curved products around a flexural center.

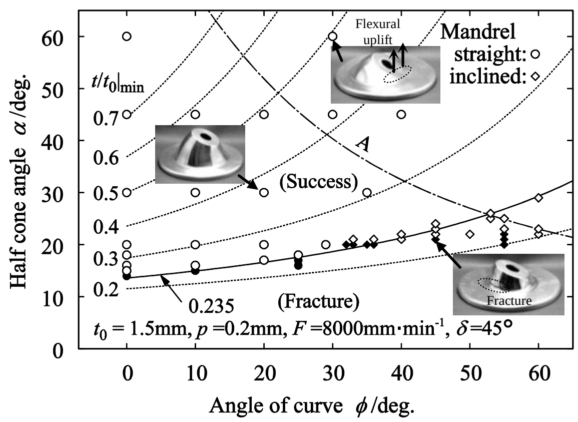


**Figure 9.** Forming results for each curve angle, $\phi$, and cone half-angle, $\alpha$, with two different mandrels, at the estimated value of the minimum thickness ratio, $t/t_0|_{min}$.

**Suppression of wall distortion.** As shown in **Figure 12a**, a distortion of the wall was observed in the outer curve at $n$ = 4, and the flange plane was twisted by 2° from the original plane. This is attributed to the combination of two factors: the accumulation of local twisting deformation at the forming point, and the direct torsion of the previously formed wall by the forming moment. Figure 12b shows the same shape formed by switching the direction of the spindle rotation alternately every 6.5 revolutions. In this experiment, the feed marks caused by the positional error of the tool were not inhibited, but the wall distortion was suppressed.

**Forming of a steel plate.** The same curved shape as shown in Figure 5b was experimentally formed from 1.0-mm-thick SPCE-SD and SUS430 steel plates at a feed rate of $p$ = 0.2 mm, as shown in **Figure 13**. To optimize the results, bi-directional tool pass, lubrication oil BM575 (for cutting; Yushiro Chemical Industries) and a tool attachment angle of $\delta$ = 0° were used. At higher speeds of the contact point, $F$, and higher feed rates, $p$, the spalling of the wall surface occurred more easily. By using viscous oil, the SPCE blank could be formed at the high speed of $F$ = 10,000 mm/min, like 1.5-mm-thick aluminum. In contrast, in the products made of SUS430, the walls had a scuff-marked glossy surface, and the speed, $F$, could not be pushed over 4,000 mm/min, since they became scratched on the flanges due to the pole of rotation of the tool.

## Conclusions

In order to enhance the flexibility of spinning, a novel sheet-spinning method using a numerically controlled spinning lathe was proposed and tested in forming experiments with hollow shells as trial products. Without using dies, several curved-shape products were successfully formed from pre-hemmed pure aluminum sheets 150 mm in diameter and 1.5 mm in thickness, by synchronizing the motion of the roller tool in the axial and radial directions with the angle of the workpiece on the spindle axis. The fundamental specifications of the present method were exemplified by the forming of curved cones with a circular cone axis. Based on a simplified deformation model, an equation which alters the sine law was proposed to estimate the wall thickness of the products, and the calculated wall thicknesses were found to nearly coincide with the measured wall-thickness distributions. The proposed method can be applied to the low-cost, rapid manufacturing of a wide variety of products in small quantities, simply by changing the tool trajectory data for the machine.

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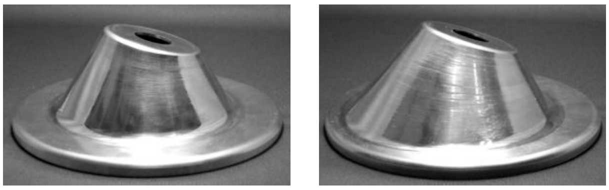
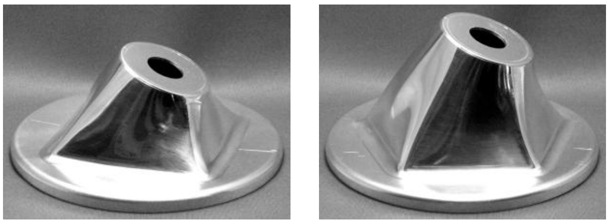
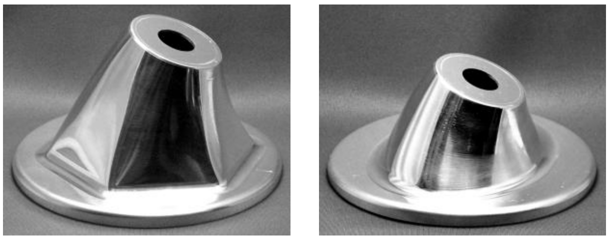


(a) Centered shape (b) Eccentric shape

**Figure 10.** Inclined-cone shells.

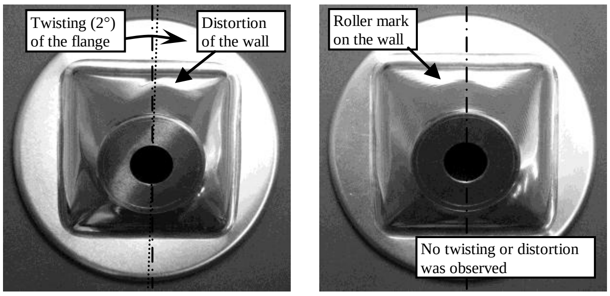


(a) Rectangle, $n$ = 4 (b) Rectangle, $n$ = 5



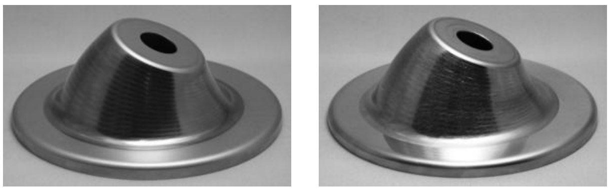
(c) Rectangle $n$ = 6 (d) Ellipse, $f$ = 0.27

**Figure 11.** Curved asymmetric products.




(a) Unidirectional rotation (b) Bidirectional rotation

**Figure 12.** Top view of the same product formed with different types of feeding (polygon, $n$ = 4).



(a) SPCE-SD $F$ = 10000 mm/min (b) SUS430 $F$ = 2000 mm/min

**Figure 13.** Curved cone products made of SPCE and SUS430.