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Robotic Metal Spinning
– Forming Non-axisymmetric Products Using Force Control –

Hirohiko Arai

Intelligent Systems Research Institute
National Institute of Advanced Industrial Science and Technology (AIST)
1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, Japan
http://staff.aist.go.jp/h.arai/   Email: h.arai@aist.go.jp

Abstract **- Metal spinning is a plastic forming process that forms a metal sheet by forcing the metal onto a rotating mandrel using a roller tool. Products formed by metal spinning have been inherently limited to round shapes. In this paper, we propose metal spinning of non-axisymmetric products by applying hybrid position/force control. The pushing force of the roller is regulated so that the roller can track the changing radius of the mandrel. Our forming experiment demonstrates that a thin aluminum sheet can be formed into a non-axisymmetric shape.**

Index Terms - Metal spinning, plastic forming, force control

I. INTRODUCTION

Metal spinning [1] is a plastic forming process that forms a metal sheet or tube by forcing the metal onto a rotating mandrel using a roller or a paddle tool (**Fig. 1**). It is widely used for producing round hollow metal parts and products. This forming process is suitable for limited production lots of a wide variety and it is particularly effective in prototyping and product development, since it needs only one mandrel which costs much less than dies for metal stamping or deep drawing. Besides the use of numerically controlled spinning machines, metal spinning is also performed manually by artisans and is known as a highly skilled manufacturing handicraft that requires decades of experience.

This study seeks to exploit robotic technologies such as force feedback control for metal spinning [2]. We aim to develop versatile and intelligent forming processes, and to expand a new application area for robotics.

While the mandrel and material rotate at high RPMs, the forming roller usually moves very slowly. Hence the products of metal spinning have been inherently limited to axisymmetric shapes that have circular cross sections around the rotation axis. Nonetheless, there has been a potential demand for products of non-axisymmetric shapes formed by metal spinning, e.g. tank ends, hoppers, exhaust pipes and lighting fixtures. Metal spinning is expected to be used more widely if it can be used to produce a variety of non-axisymmetric products. Gao et al. proposed a spinning machine for elliptical cross section products [3]. Sango Co., Ltd. succeeded in metal spinning of pipes with eccentric or oblique axes [4]. However, both methods require a specially designed spinning device for each shape.

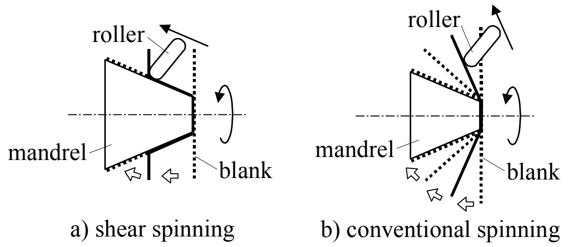


Fig. 1 Metal spinning

In this paper, we present a metal spinning process for non-axisymmentric products by controlling the pushing force of the forming roller. Hybrid position/force control is applied so that the roller follows the contour of the non-axisymmetric mandrel while moving in the direction of the mandrel axis. Our forming experiment demonstrates that a thin aluminum sheet can be spun into the same shape as the mandrel.

II. METAL SPINNING USING HYBRID POSITION/FORCE CONTROL

We recently proposed the application of hybrid position/force control for shear spinning, in which the roller was moved along the surface of the mandrel and the material was squeezed onto the mandrel [2].

The forming roller of a conventional NC spinning machine is usually controlled using high-gain position feedback. The clearance between the roller and the mandrel must be exactly controlled to the wall thickness of the product after the forming process. In the control of the spinning machine, this clearance was the most difficult of the various forming parameters to decide. The setting of the clearance fairly depends on the experience of the operators, and it must be adjusted after they perform some forming trials.

However, it is possible to obtain the desired shape of the product by fitting the material tightly against the mandrel. This can be accomplished by pressing the material onto the mandrel with appropriate force, instead of leaving a clearance between the mandrel and the roller equal to the wall thickness. In Ref. [2], hybrid position/force control was used for shear spinning of a conical product. The forming roller was position-controlled in a constant velocity in the feeding direction parallel to the mandrel surface. The pushing force of the roller normal to the mandrel was controlled to a constant value. This method frees the metal spinning process from requiring the fine adjustment of the clearance between the mandrel and roller.

In this paper, we extend this method for metal spinning of non-axisymmetric products by applying force feedback control. A non-axisymmetric mandrel of a desired shape was used here. The pushing force of the forming roller was controlled and the material was forced onto the mandrel.

The roller follows the contour of the mandrel to fit the material to the mandrel. This enables a non-axisymmentric product of the same shape as the mandrel to be fabricated.

Our method does not need a specially designed mechanism to cope with each cross section shape. Various non-axisymmetric shapes can be easily spun by replacing the mandrel. Since the shape of the product is determined by the shape of the actual mandrel, large amount of data on the 3-dimensional shape are not required for control.

For a non-axisymmetric product, the contact between the roller and mandrel should be considered in a 3-D space. If the feeding direction of the roller is parallel to the mandrel surface, in the same way as in Ref. [2], the trajectory of the roller departs from the plane of the blank and the flange might be deformed. Consequently, the projection of the roller velocity onto the mandrel axis, V_X, is controlled to the desired constant value, V_{Xd}. The force component of the roller normal to the mandrel axis, F_Y, is controlled so that the component normal to the mandrel surface, F_n, is regulated to the contant value, F_{nd} (**Fig. 2**). The control law is represented as;

$$\boldsymbol{f} = \begin{bmatrix} f_x \\ f_y \end{bmatrix} = \boldsymbol{f_P} + \boldsymbol{f_F} \quad (1)$$

$$\boldsymbol{f_P} = \boldsymbol{MJ}^{-1} \begin{bmatrix} k_{vX}(V_{Xd} - V_X) + k_{pX}(V_{Xd}t - X) \\ 0 \end{bmatrix}$$

$$\boldsymbol{f_F} = \boldsymbol{J}^T \begin{bmatrix} 0 \\ cF_{nd} + k_{pF}(F_{nd} - F_n) + k_{iF}\int (F_{nd} - F_n)dt \end{bmatrix}$$

where f_x and f_y are actuator thrusts, $\boldsymbol{M}$ is the mass matrix of the actuators, $\boldsymbol{J}$ is Jacobian matrix between the actuator frame and XY-frame, c is a positive coefficient, and k_{vX}, k_{pX}, k_{pF}, k_{iF} are feedback gains.

III. Forming Experiments

Figure 3 illustrates our experimental setup. The linear motion of the x and y axes was driven by ball-screws (2 mm/rev) and DC servo motors (60 W). The mandrel (θ axis) was rotated by a DC servo motor (120 W) with a planetary gear (reduction rate: 1/10). The θ axis was slanted relative to the x axis by 60 deg. The diameter of the forming roller was 70 mm. The roundness of the edge was a 9.5 mm radius. The roller was made from alloy tool steel (AISI D2, quenched). A 6-axis force/torque sensor was equipped at the roller holder. A personal computer (Pentium, 233 MHz) received the encoder and force sensor signals via interface boards, and sent torque commands to the motor drivers via a D/A board. The sampling interval for the control was 1 ms.

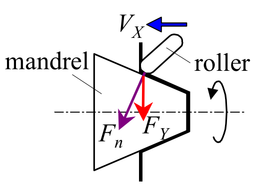


Fig. 2 Hybrid position/force control

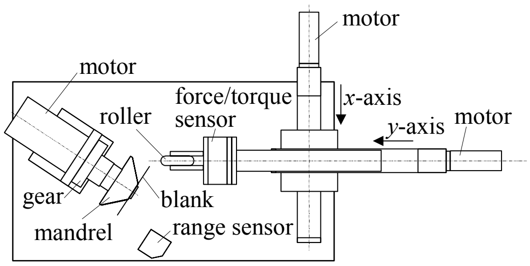


Fig. 3 Experimental setup

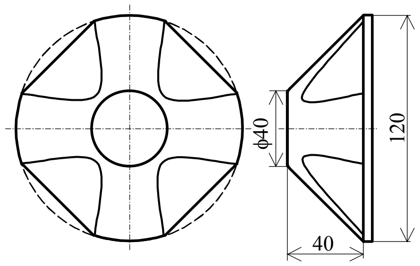


Fig. 4 Mandrel #1

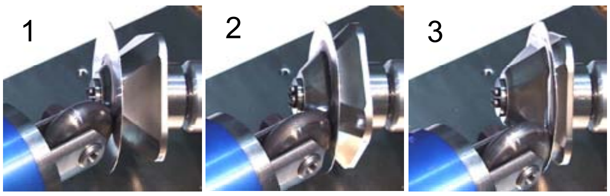


Fig. 5 Forming process

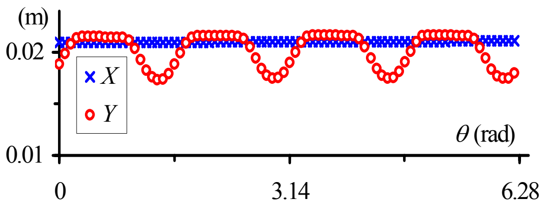


Fig. 6 Position of roller

Two types of non-axisymmetric mandrels were prepared. **Figure 4** shows Mandrel #1 (stainless steel, AISI 304). The side surface of a conical mandrel with a 45 deg half angle was partly machined by wire-cut EDM (Electrical Discharge Machining) into flat planes. The cross section normal to the mandrel axis was composed of circular arcs and straight lines. The blank was a round disc of pure aluminum (1050A-O, annealed) with a 120 mm diameter and 0.78 mm thickness.

Figure 5 shows our forming process using Mandrel #1. The feed rate of the roller in axial direction, V_X, was 0.0177 mm/s, and the mandrel speed was 7.5 rpm (π/4 rad/s). The roller feed for one turn of the mandrel, ΔX, was 0.141 mm/rev. The pushing force F_n of the roller was controlled to 400 – 450 N, in which the direction of F_n was fixed normal to the conical surface, i.e. at 45 deg from the mandrel axis.

Figure 6 shows the displacement of the roller in the X direction (parallel to the mandrel axis) and Y direction (normal to the mandrel axis). In spite of the uneven radius of the mandrel, the disturbance of X was very small and the roller was fed at a constant velocity. But, Y was changed so that the roller could accurately track the mandrel surface.

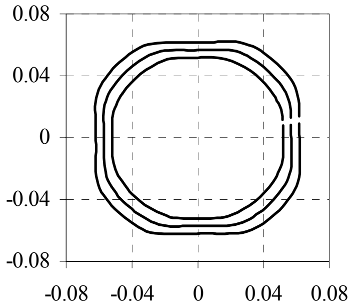


Fig. 7 Path of roller

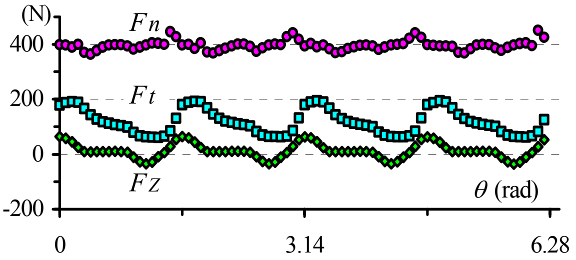


Fig. 8 Forming force

Figure 7 illustrates the path of the center of the roller relative to the mandrel. The roller moved along the contour of the mandrel.

Figure 8 shows the forming force of the roller applied to the material when the desired force F_{nd} was 400 N. F_n is the normal force component against the mandrel surface, F_t is the tangential component along the roller movement, and F_Z is the tangential component to the mandrel rotation. F_t and F_Z changed especially when the roller passed the planar part of the mandrel surface. The roller and the mandrel obliquely contacted at this position, and the contact angle changed as the mandrel rotated. The pushing force of the roller, F_n, was maintained around 400 N by the force feedback control.

When the pushing force exceeded 450 N, the rotation of the mandrel sometimes stopped due to insufficient motor torque. While forming near the bottom of the product, where the radius of the forming point was large, the tangential force F_Z overcame the motor torque of the mandrel. The mandrel motor should have enough torque to form a non-axisymmetric shape. When the sign of F_Z changed, the torque exerted to the mandrel from the roller reversed the direction. At that time, impact noise due to backlash was observed from the gear of the mandrel motor. Reduction gears with small backlash are preferred to avoid product failure and damage of the gear caused by such impact.

Figure 9 shows the mandrel and the completed product. The planar part machined from the conical shape was also correctly formed to match the mandrel. The flatness of the flange was maintained fairly well. The profiles of the product and the mandrel at the planar part were compared using a laser displacement sensor (**Fig. 10**). The springback was small and the product tightly fitted the mandrel.

Fig. 9 Mandrel #1 and product

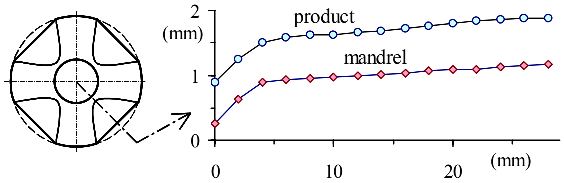


Fig. 10 Profile of product

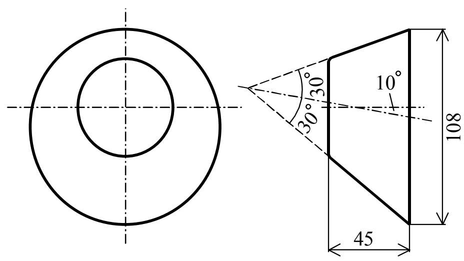


Fig. 11 Mandrel #2

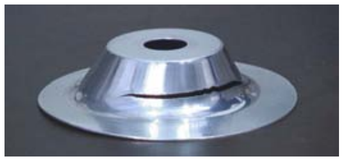


Fig. 12 Example of fracture

The wall thickness of the product was 0.55 – 0.56 mm at the conical part and 0.44 – 0.46 mm at the planar part. In shear spinning, the wall thickness t of the product can be estimated as,

$$t = t_0 \sin \alpha \tag{2}$$

when the thickness of the blank is t_0, and the angle between the side surface and the axis of the mandrel is α. As $\alpha = 45$ deg at the conical part and $\alpha = 35$ deg at the planar part, the wall thickness calculated from Eq. (2) was 0.55 mm and 0.45 mm, respectively, and coincided fairly well with the actual thickness.

Figure 11 illustrates Mandrel #2 (carbon steel, AISI 1045). A cone with a 30 deg half-angle was slanted by 10 deg and the top and bottom were wire-cut by EDM. The mandrel axis was eccentric and the cross section normal to the axis was elliptic. The maximum angle between the side surface and the mandrel axis was 40 deg, and the minimum angle was 20 deg.

Shear spinning using this mandrel sometimes resulted in the wall fracture of the product. In **Fig. 12**, the pushing force F_n was 400 N, the mandrel speed was 15 rpm, and the roller feed ΔX for one turn of the mandrel was 0.15 mm/rev. A tensile fracture occurred during the forming at the wall on the 20 deg side.

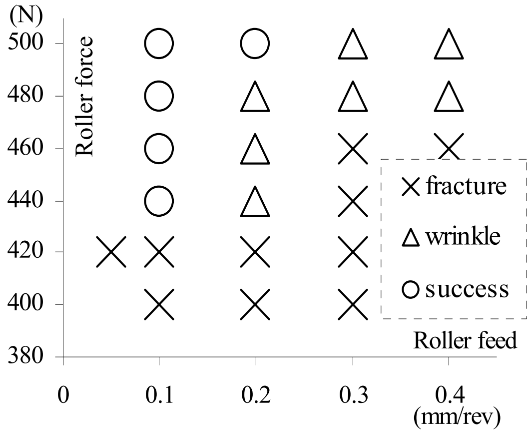


Fig. 13 Effect of pushing force vs. roller feed


Fig. 14 Mandrel #2 and product

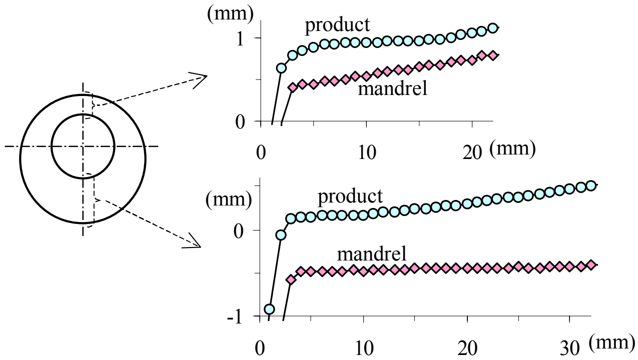


Fig. 15 Profile of product

We performed a series of forming tests varying the pushing force of the roller F_n and the roller feed ΔX (**Fig. 13**). The mandrel speed was 15 rpm. "○" means that the product was formed successfully. "×" represents the occurrence of a fracture at the 20 deg wall. "△" means a wrinkle occurred at the flange on the 40 deg side.

We found that product failures such as fractures and wrinkles could be prevented by increasing the pushing force at the same mandrel speed and roller feed. We suppose that the pushing force helps shear deformation of the material and decreases the radial tensile stress that causes fracture of the wall and buckling of the flange. **Figure 14** shows the completed product and Mandrel #2.

The profiles of the product and the mandrel at the 20 deg and 40 deg longitudinal sections were compared using a laser displacement sensor (**Fig. 15).** The pushing force F_n was 500 N and the roller feed ΔX was 0.1 mm/rev. The formed product generally matched the mandrel overall, although the material was slightly displaced from the mandrel near the top of the 20 deg wall, and some springback was observed near the bottom of the 40 deg wall.

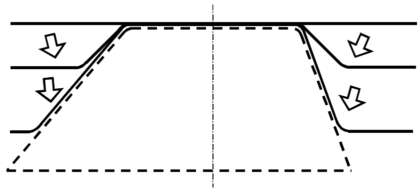


Fig. 16 Two-pass spinning

The wall thickness of the product was 0.50 – 0.52 mm at the 40 deg section. This coincided fairly well with the thickness calculated from Eq. (2), which was 0.50 mm. On the other hand, the thickness of the 20 deg section was not uniform; it was 0.30 – 0.35 mm near the top and 0.20 – 0.22 mm near the bottom. The thickness from Eq. (2) was 0.27 mm. Reminded of the shape error near the top, we supposed that the pushing force (500 N) was insufficient. Stronger pushing force applied to the material might be necessary for more uniform spinning.

As another method to prevent wall fractures, we also tried two-pass spinning (**Fig. 16**). First, a cone with a 45 deg half-angle was formed as an intermediate product by shear spinning using position control with the material not contacting the mandrel surface. Then the forming roller was used to press the material onto the mandrel using force control to finish the product. The mandrel speed and the roller feed were 240 rpm and 0.05 mm/rev for the first pass and 30 rpm and 0.2 mm/rev for the second pass, respectively. Although the pushing force F_n in the second pass was 400 N, the wall fracture did not occur as it did in one-pass shear spinning. It is advantageous to have the spinning succeed with weaker pushing force.

The wall thickness of the product at the 20 deg side was 0.47 – 0.50 mm near the top and 0.32 – 0.35 mm near the bottom. The thickness at the 40 deg side was 0.52 – 0.55 mm near the top and 0.50 – 0.52 mm near the bottom. The difference of the wall thickness of the 20 deg side and the 40 deg side decreased in comparison with the sine law of Eq. (2).

IV. Reduction of Forming Time

Reduction of the forming time is a very important issue for the practical application of our proposed method. The forming time is represented as; (height of product) ÷ (roller feed for one turn of mandrel) ÷ (mandrel speed). When spinning non-axisymmetric products, the mandrel speed should be kept slower than when spinning axisymmetric products, and this results in a long forming time. For example, it takes 20 minutes to spin a product of 30 mm in height with roller feed 0.1 mm/rev and a mandrel speed 15 rpm. Actually, it took 10 – 30 minutes in our forming experiments described in the previous section, so the forming time must be significantly shortened.

The roller moves forward and backward to follow the contour of the mandrel while a non-axisymmetric product is being spun. However, if the mandrel speed is high, the roller cannot keep pace with the shape of the mandrel. The response of the force feedback oscillates due to actuator saturation, and the surface of the mandrel becomes rough, or the pushing force on the material is inadequate and the product is separated from the mandrel. Such failures were observed at mandrel speeds over 15 rpm for Mandrel #1 and 30 rpm for Mandrel #2 in our experiments.

On the other hand, a larger roller feed can be selected as the roller pushes the material with stronger force (see Fig. 12). However, using a too strong pushing force when spinning a non-axisymmetric product disturbs the rotation of the mandrel, as was observed with Mandrel #1. The pushing force cannot be so strong when the mandrel motor does not have enough torque capability.

This problem can be solved by mechanical design of the spinning machine, i.e. choice of more powerful motors with adequate rated torque. The motors that drive the roller should have high power rate with low rotor inertia, and the pitch of the ball-screw should be larger. Then the pushing force of the roller can be stronger and the roller feed can be larger. Even when the mandrel rotates faster, the roller speed can keep pace with the movement of the mandrel.

On the other hand, we could also implement some control algorithms for the roller and mandrel to shorten the forming time to some extent, although doing so would be a supplementary solution. It would be more effective if such a control method were used together with an improved apparatus. In this section, we discuss a control method for reducing the forming time.

The cross section of Mandrel #1 near the top is a circle, and that of Mandrel #2 is an ellipse which is very close to a circle in shape. Therefore, the movement of the roller following the mandrel contour is very small just after forming starts using these mandrels. The speed and torque of the motor driving the roller are adequate. Consequently, it is possible to rotate the mandrel at a higher speed when such a part is formed.

In contrast, the roller moves with greater amplitude near the bottom of the product since unevenness of the cross section radius becomes larger. Failures tend to arise at this position because the roller actuators are inadequate. The mandrel speed should be limited at such positions.

The main concept of our control method is to adjust the mandrel speed, which is generally fixed in NC spinning machines. The mandrel speed is increased where the roller movement in the radial direction is small, and it is restricted where the roller movement is large. The forming characteristics in shear spinning using force control are mainly determined by the pushing force F_n and the roller feed ΔX. Hence F_n and ΔX are kept constant while the mandrel speed $\dot{\theta}$ changes according to the amplitude of the roller movement. The feed rate of the roller V_X is $\Delta X\dot{\theta}$. The forming time is thus shortened overall, since the total turns of the mandrel, (height of product) $\div$ (roller feed), are constant.

As the basis for adjusting the mandrel speed, we consider the following relationship.

$$\dot{Y}^2 + K\dot{\theta}^2 = V \qquad (3)$$

where K and V are positive constants. Equation (3) means that the tangential velocity of the roller and the mandrel in the normalized actuator space is constant. Since the roller always contacts the mandrel, Y can be represented as a function $Y(\theta)$. Therefore,

$$\dot{Y} = \frac{dY}{d\theta}\dot{\theta} \qquad (4)$$

$dY/d\theta$ is determined by the cross section shape of the mandrel and represents the change of the roller position Y due to the rotation of the mandrel. Substituting Eq. (4) into Eq. (3), the mandrel speed is;

$$\dot{\theta} = \sqrt{V \Big/ \left\{ \left(\frac{dY}{d\theta} \right)^2 + K \right\}} \qquad (5)$$

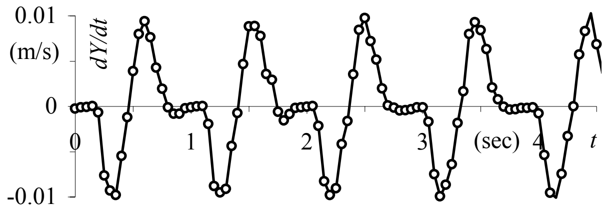
The mandrel speed becomes lower as $dY/d\theta$ becomes larger. The mandrel speed is at its maximum value when the cross section of the mandrel is a circle and Y does not change ($dY/d\theta$=0). K is a coefficient for normalization and can be determined from $\dot{Y}$ and $\dot{\theta}$ at the rated speed of each motor. If the maximum mandrel speed is $\dot{\theta}_{MAX}$, V is calculated as $V = K\dot{\theta}_{MAX}^2$.

Let us then consider what data should be used as $dY/d\theta$ in Eq. (5). From Eq. (4), $dY/d\theta$ can be calculated in real-time from $\dot{Y}$ and $\dot{\theta}$ as $dY/d\theta = \dot{Y}/\dot{\theta}$. On the other hand, it is preferred that the mandrel speed is varied rather slowly. An abrupt change of the mandrel speed would lead to the large inertial torque of the mandrel motor and also cause large acceleration of the roller. Consequently, the average of $(dY/d\theta)^2$ for one rotation of the mandrel is substituted into Eq. (5) to obtain the mandrel speed.

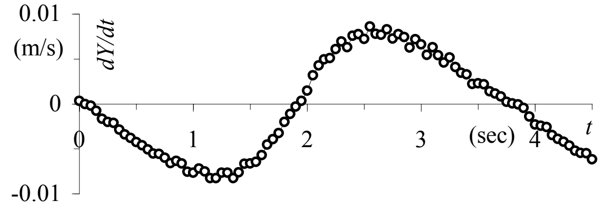
The memory required for this method is much smaller than that of the 3-dimensional shape data of the whole mandrel, since only one-dimensional data of $(dY/d\theta)^2$ for one rotation is used. In addition, the data can be acquired in real-time while forming, and the pre-measurements before processing are unnecessary.

We conducted a forming experiment using Mandrel #2 applying the above adjustment method of the mandrel speed. The hybrid position/force control law was almost the same as Eq. (1), except that the roller velocity V_X changed proportional to the mandrel speed. The pushing force of the roller was 480 N, and the roller feed was 0.1 mm/rev.

Figure 17 shows the radial velocity of the roller, $\dot{Y}$, while forming at a height of (a) 5mm and (b) 20 mm from the top. The mandrel speed was automatically adjusted to (a) 64.3 rpm and (b) 16.0 rpm, respectively. Though the amplitude of the roller movement was greater in (b), the peak velocity of the roller was about $\pm$ 0.01 m/sec in both cases due to the change of the mandrel speed. In addition, we verified that quality of the product, such as the precision and wall thickness, was not affected by this control method.



(a) 5mm from top



(b) 20mm from top

Fig. 17 Velocity of roller

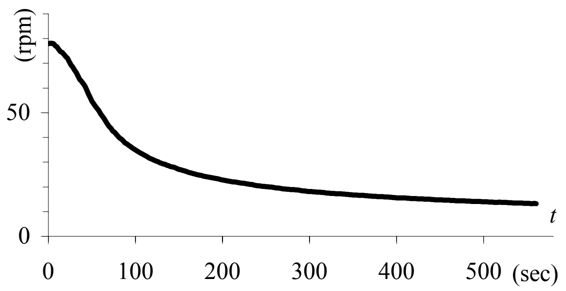


Fig. 18 Change of mandrel speed

Figure 18 shows the change of the mandrel speed while forming. The total forming time was 569.6 sec. The minimum mandrel speed, which was determined by the most extreme roller movement, was 13.2 rpm. If the spinning were performed at a constant mandrel speed 13.2 rpm, it would have taken 1100.6 sec to complete. Thus, the forming time was effectively reduced by about half.

V. CONCLUSIONS

We presented our method for metal spinning of non-axisymmetric products using hybrid position/force control. We confirmed in experiments that the roller followed the contours of the non-axisymmetric mandrel and a product of the same shape as the mandrel could be formed. We also proposed a method for adjusting the mandrel speed to reduce the forming time, and verified the effectiveness of our method.

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