Robotic Metal Spinning

– Shear Spinning Using Force Feedback Control –

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Abstract

Metal spinning is a plasticity forming process that forms a metal sheet or tube by forcing the metal onto a rotating mandrel using a roller tool. This is a study on metal spinning applying robot control techniques such as force feedback control with the aim to develop flexible and intelligent forming processes, and to expand a new application area for robot control. An experimental setup was developed for gathering basic data on the forming process. Some results of preliminary experiments are presented. The influence of the clearance between the roller and mandrel is also discussed. The author proposes applying hybrid position/force control for shear spinning, which is free from fine adjustment of the clearance. The effectiveness of the proposed method was experimentally verified.

1 Introduction

This study seeks to exploit robot control techniques such as force feedback control for *metal spinning.* We aim to develop flexible and intelligent forming processes, and to expand a new application area for robot control.

Metal spinning is a plasticity 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, e.g. tableware, kitchenware, ornaments, lighting fixtures, parabola antennas, boilers, tanks, gas canisters, nozzles, engine parts, and tire wheels. This forming process is also known as a highly-skilled manufacturing craft by artisans that requires decades of experience. Even nose cones for H2 space rockets launched by NASDA in Japan are produced by such manual metal spinning.

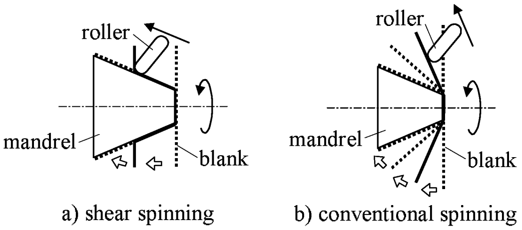

Fig. 1: Metal spinning

Metal spinning has several merits over other metal forming processes as follows.

- It can create more complicated shapes than sheet metal stamping or deep drawing.
- As it needs only one mandrel, it is easier to set up for forming.
- Forming force is rather small and the forming apparatus can be compact.
- Material can be saved in comparison with cutting processes.
- It can provide precision products and good surface finishing.

These merits agree with recent trends in production technologies such as rapid prototyping and net shape manufacturing. Metal spinning can also be regarded as one of the incremental forming processes, which have been recently receiving attention in plasticity forming technologies.

However, progress in automated metal spinning is rather slower than in other areas of plasticity forming. Although numerically controlled spinning machines can achieve mass production of simple-shaped products, the programming of the machines depends greatly on skilled operators. Scientific research on metal spinning, mainly in production and material engineering, also does not seem very active. The mechanism of deformation is three-dimensional and too complicated for computer simulations. There are many control parameters and it requires the development of experimental setups. Consequently, the mechanics of the forming process have not been sufficiently clarified. In particular, forming procedures for *conventional spinning* have not been theoretically established. In fact, practical production depends on the experience of skilled workers.

Here we briefly review several previous studies on metal spinning. Hayama, who pioneered the earliest studies in this field, theoretically and experimentally investigated forming conditions of *shear spinning* [1, 2] and also studied the forming procedures of conventional spinning [3]. Kawai proposed building a database of forming examples and using it to select forming parameters [4]. Shima proposed flexible spinning, in which two rollers pinched the material and no mandrel was necessary [5]. Katupitiya proposed a metal spinning system that integrated human skills into an automated forming process [6].

In recent years, studies on industrial robots for manufacturing applications tend to be less and less active while most academic researchers are inclined towards non-manufacturing applications. In consequence, applications for industrial robots have not varied much from the conventional handling, assembly, welding and painting. Some researchers even consider industrial robots as mature or old-fashioned technology since they only take notice of such applications.

Current industrial robots are generally used for simple repetitive tasks of low added value, which substitute for unskilled factory workers. Such robots have value only if they are less expensive and used in mass production to achieve higher speed and yield. However, mass production is not the only form of operation in manufacturing industries. There are various types of manufacturing crafts that only experienced artisans can perform. Such crafts are usually of small quantity but can create high value added products. A new market for robot technologies might develop if robotics researchers were attracted to such areas, utilizing the potentials of accumulated techniques, e.g. sensory feedback control, to achieve valuable application tasks for which even expensive intelligent robots can be worthwhile.

Force feedback control of manipulators has been studied in robotics for many years. We now have a variety of theoretical and experimental knowledge on hybrid position/force control, impedance control, etc. However, these techniques have not been widely applied in practice except for only a few kind of tasks such as assembly and grinding. We must still seek effective applications for these control methods.

Metal spinning appears to be a suitable task for an industrial robot for several reasons. In manual metal spinning, the various senses of the worker, particularly force feeling via the tool, play an important role. Metal spinning needs much smaller forming force than other plasticity forming techniques, on the order of kilograms instead of tons, because it is based on local deformation. It involves many control parameters and needs dexterous motion with multiple degrees of freedom. It is suitable for limited production of a wide variety and is a process of high added value, which we can see from the fact that even manual production can be viable as a manufacturing business. Thus it is expected that the profitability of a force controlled industrial robot can be high.

In this research, we aim to make metal spinning more flexible and intelligent, by introducing robot control technologies, such as force control, into the forming process. The forming conditions are modified in real time based on feedback of the forming status to avoid forming defects and to obtain high-quality products.

Conventional robot tasks are mainly composed of *moving* an object. In contrast, this research encounters the novel aspects of *transforming* an object. We expect that challenging research subjects may develop from this research while utilizing the potentials of robot technologies developed so far.

The remainder of this paper is organized as follows. In Section 2, we describe an experimental setup for gathering basic forming data. The preliminary experimental results are shown in Section 3. We discuss the problem of clearance setting between the mandrel and roller in Section 4. In Section 5, we propose applying hybrid position/force control to metal spinning, and experimentally verify the effectiveness of our proposed control method.

2 Experimental setup

First, we developed an experimental setup for conducting basic experiments on metal spinning. Forming of different materials under various parameters can be done to gather forming data, e.g. success or failure of forming, precision of product, wall thickness, surface roughness, and forming force. In particular, generation of defects (wrinkles or breaks) can be analyzed by monitoring the conditions around their occurrence.

Figure 2 illustrates our experimental setup. The linear motion of x and y axes is driven by the ball-

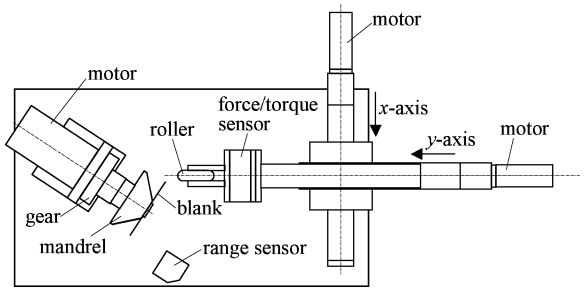

Fig. 2: Experimental setup

Table 1: Specifications of each axis

	x, y axis	θ axis
Rated Force/ Torque	580 N	3.9 Nm
Rated Speed	100 mm/s	250 rpm
Resolution	0.5 μm/pulse	0.009 deg/pulse

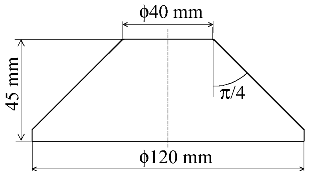

Fig. 3: Mandrel

screws (2 mm/rev) and DC servo motors (60W). The mandrel (θ axis) is rotated by a DC servo motor with a planetary gear (reduction rate: 1/10). The θ axis is slanted relative to the x axis by $\pi/3$ rad. Each motor has an incremental encoder (4000 p/r) for detecting the rotation angle. The specifications of each axis are listed in **Table 1**.

The diameter of the forming roller is 70 mm. The roundness of the edge is a 9.5 mm radius. The roller is made from alloy tool steel (AISI D2, quenched). A 6-axis force/torque sensor is equipped between the roller and y axis. The shape of the mandrel is illustrated in **Fig. 3**. The material of the mandrel is stainless steel (AISI 304). A laser range sensor measures wrinkles in the flange. The sensing resolution is 0.18 mm within a range of 40 to 120 mm.

A personal computer (Pentium, 233 MHz) receives the signals from the encoders, the force sensor and the range sensor via interface boards, and sends torque commands to the motor drivers via a D/A board. The sampling interval for the control is 1 ms.

3 Preliminary experiments

We conducted preliminary experiments to gather basic forming data using the setup described above. We first tried shear spinning, in which the roller was moved along the surface of the mandrel and the material was squeezed onto the mandrel. The blank was a round plate of pure aluminum (1100A-O, annealed) with a 120 mm diameter and 0.78 mm thickness.

In shear spinning, it is known that the wall thickness t of the product is represented as,

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

where t_0 is the thickness of the blank, and α is the angle between the side surface and the rotating axis of the mandrel. In our experiment, $t = 0.55$ mm since $t_0 = 0.78$ mm and $\alpha = \pi/4$ rad. The clearance between the mandrel and roller was set to 0.55 mm. The surface of the roller was lubricated with liquid lubricant (CRC5-56).

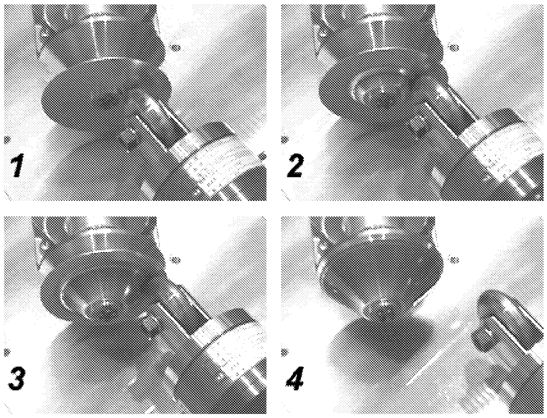

Fig. 4: Forming experiment

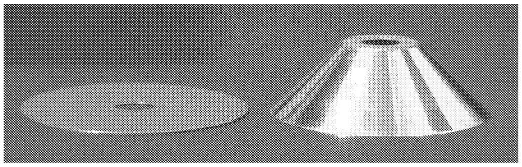

Fig. 5: Blank and product

Each axis was controlled using simple high-gain PD feedback control. The x and y axes were controlled so that the roller moved along a straight line parallel to the surface of the mandrel at a constant velocity. The mandrel (θ axis) was also rotated at a constant angular velocity. The position and motor current of each axis, force at the roller, and range sensor signal were recorded during forming.

Figure 4 shows the forming experiment. **Figure 5** shows an example of the blank and the finished product. The product was formed to the shape of the mandrel.

Next, the forming force applied to the material by the roller was measured. The force component in line with the movement of the roller is defined as F_X, the normal force component against the surface of the mandrel is defined as F_Y, and the tangential component to the mandrel rotation is defined as F_Z (**Fig. 6**). F_X, F_Y and F_Z are plotted for the displacement X of the roller along the mandrel (**Fig. 7**). The velocity of the roller in the X direction was 0.1 mm/s, and the angular velocity of the θ axis was 120rpm (4π rad/s). The movement of the roller for one turn of the mandrel was 0.05 mm/rev.

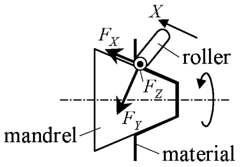

Fig. 6: Force components at roller

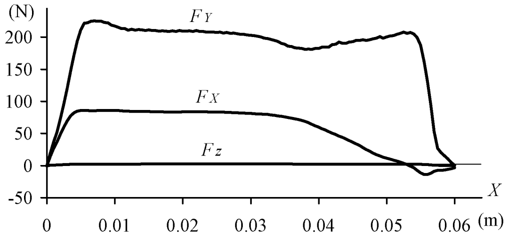

Fig. 7: Forming force

F_Y, which forces the material onto the mandrel, was about 200N constantly. The feeding force of the roller, F_X, was about 80N at first, and later decreased gradually as the forming proceeded. As the width of the flange, i.e. the remaining unformed blank, became narrower, the stiffness of the flange reduced and the resistant force became weaker. The tangential force F_Z was about 3N maximum, and was much smaller than F_X and F_Y. We can see the forming force is so small that it can be applied by an industrial robot. It was also confirmed that the motor current was much smaller than the rated value and the torque of each motor had an adequate margin.

When the velocity of the forming roller is too large, wrinkles are generated at the flange due to buckling. The wrinkles disturb the uniform forming and degrade the quality of the product. Moreover, deep wrinkles might block the movement of the roller and make the forming impossible. **Figure 8** shows an example of the forming result when wrinkles occurred.

Growth of the wrinkles was experimentally investigated using a laser range sensor. **Figure 9** shows height of the flange at 5 mm from the outer edge. The velocity of the roller in X direction was 0.1mm/s and the angular velocity of the θ axis was 60rpm (2π rad/s). The roller moved 0.1 mm for one turn of the mandrel. The height of the flange from the attachment plane was measured during one turn for every 25 turns of the mandrel.

In the early phase of the forming (No. 1 to 6), the flange remained almost flat. As the forming progresses (No. 7 to 12), the shallow wrinkles slowly grew deeper. The stiffness of the narrow flange was insufficient to keep it flat.

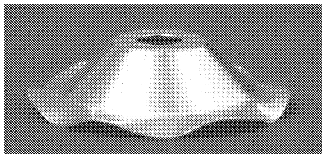

Fig. 8: Wrinkled flange

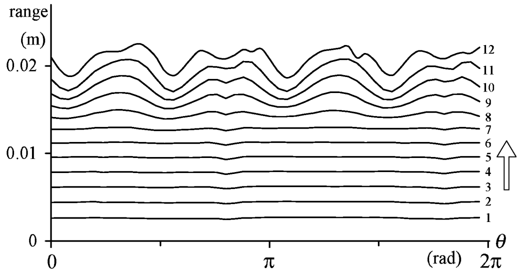

Fig. 9: Growth of wrinkles

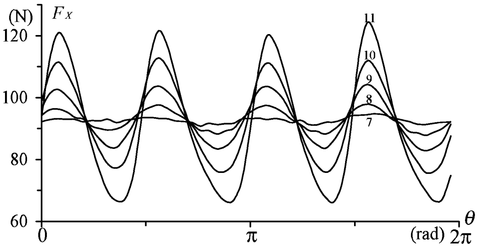

Fig. 10: Fluctuation of feeding force

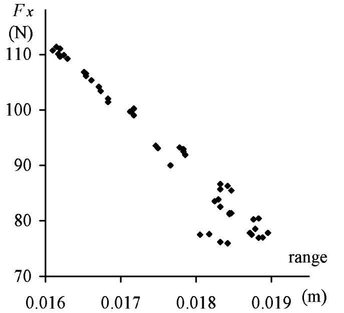

Fig. 11: Wrinkles and feeding force

The forming force was measured while the wrinkles were generated. **Figure 10** shows the feeding force F_X for the data of No. 7 to 11. As the wrinkles became deeper, the fluctuation of the feeding force increased. In **Figure 11**, F_X is plotted for the height of the flange during one turn (No. 10), where the phase of the θ axis was mutually shifted by π rad as the range sensor was located at the opposite side of the roller. The unevenness of the flange and the fluctuation of the feeding force are related almost linearly. Therefore, the growth of the wrinkles can be detected from the feeding force.

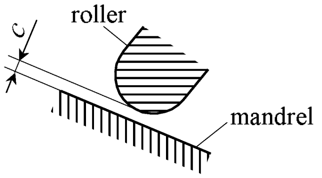

Fig. 12: Clearance between mandrel and roller

4 Clearance between mandrel and roller

Among the various forming parameters in metal spinning, the clearance between the mandrel and roller (**Fig. 12**) can be considered the most difficult to set, in view of controlling the forming machinery. In shear spinning, the wall thickness after the process is represented as Eq. (1), and the clearance should be exactly controlled equal to the thickness. When the clearance is too large, the precision is degraded because the material does not fully contact the mandrel. This upsets stable forming and wrinkles are likely to occur. Conversely, too small a clearance makes the forming force very large, and the flow of the material sometimes improperly deforms the product.

To obtain an appropriate clearance, the position of the roller relative to the mandrel must be strictly calibrated. The profile of the mandrel should also be exactly known. In addition, the roller should track the desired trajectory precisely under the forming force. When the stiffness of the machinery is insufficient, as is often the case with industrial robots, the set clearance cannot be maintained due to elastic distortion resulting from the forming force.

As the mandrel used in this study is a simple conical shape, the wall thickness of the product can be easily predicted from Eq. (1). However, it is difficult to know the exact distribution of the thickness if the shape of the mandrel is more complicated, e.g. when the inclination of the surface changes irregularly. In multi-pass conventional spinning, in which the material is formed in steps to fit the mandrel, the final thickness distribution is more difficult to estimate. The setting of the clearance fairly depends on the experience of the operators, and it should be adjusted after some forming trials.

We experimented on shear spinning under different clearance settings and compared the results. The theoretical wall thickness was $0.78 \sin \pi/4 = 0.55$[mm] from Eq. (1). The feeding velocity $\dot{X}$ of the roller was 0.1 mm/s and the angular velocity $\dot{\theta}$ of the mandrel was 60rpm, as in the example of the previous section. We tried four values for the clearance, $c = 0.25$ mm, 0.40 mm, 0.55 mm and 0.70 mm.

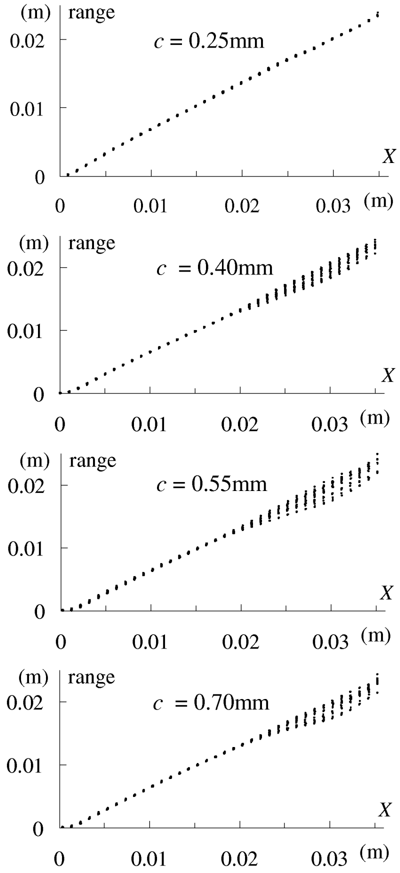

Fig. 13: Height of flange

Figure 13 shows the height of the flange measured by the laser range sensor. The data during one turn were plotted for every 10 turns of the mandrel. The forming was completed without wrinkles when $c = 0.25$ mm. At other clearance settings, the amplitude of the unevenness started to increase (the plot scattered) and wrinkles were generated.

The pushing force F_Y is compared in **Fig. 14**. The smaller the clearance was set, the larger F_Y became. The interior surface of the product was pressed onto the mandrel and appeared glossy when $c = 0.25$ mm. On the other hand, the surface finish of the blank sheet (fine scratches) remained when $c \geq 0.4$ mm. As the material separated from the mandrel, the precision of the product deteriorated.

Figure 15 shows the feeding force F_X of the roller. F_X oscillates when $c \geq 0.4$ mm and it also indicates the generation of wrinkles. When $c = 0.25$ mm, the feeding force is rather smaller than in other cases.

The clearance of 0.25 mm led to the best result, when the clearance is assumed to be too small. We also measured the actual wall thickness of the products using a micrometer. When $c = 0.25$ mm, the thickness was 0.55mm to 0.56 mm and nearly equaled to the

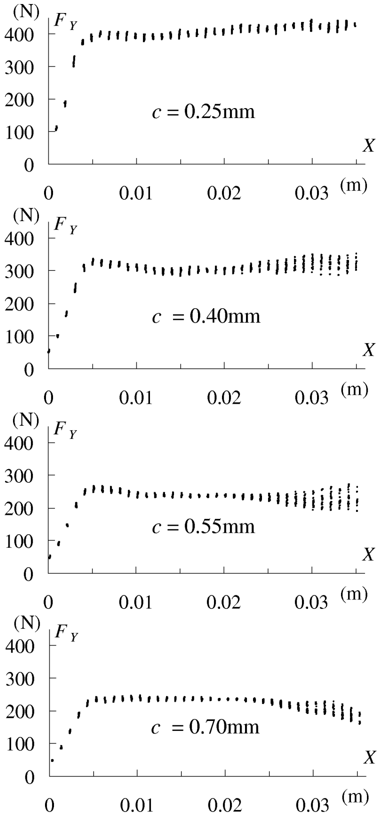

Fig. 14: Pushing force F_Y

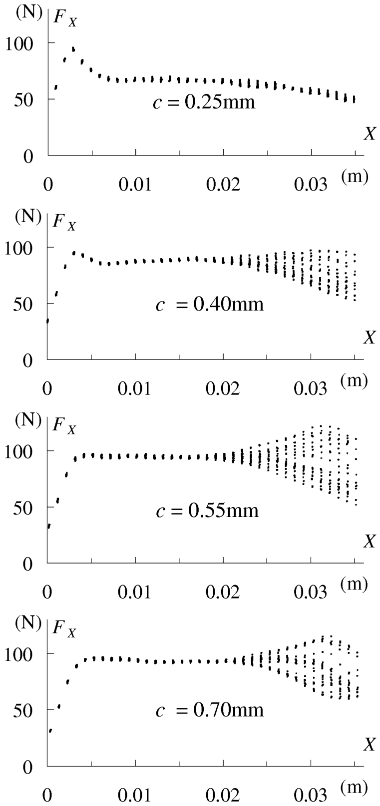

Fig. 15: Feeding force F_X

value from Eq. (1). It is supposed that the clearance of 0.25 mm was not actually achieved and the clearance enlarged nearly to the theoretical wall thickness because of the deformation arising from the forming force. As the deviation of the roller pass caused by servo error was 0.04mm maximum, the mechanical deformation was dominant. For $c = 0.55$ mm, which is nearest to the theoretical wall thickness, the deformation made the real clearance larger than the desired value and caused the wrinkles. The actual wall thickness was 0.59 mm to 0.62 mm near the flange and thicker than the theoretical value.

These results demonstrate that the clearance setting significantly affects the quality of the forming process. It might be preferable to set a smaller clearance than the theoretical value of Eq. (1) when the machinery does not have high stiffness. However, as the proper setting is dependent on the machinery and the formed object, some forming trials will be necessary. In contrast, when the machinery is very stiff, the clearance setting will be more critical and the roller should be controlled very precisely relative to the mandrel. In particular, when a thin sheet is spun, the admissible clearance will be severely restricted.

5 Force feedback control

The problems with the clearance setting discussed in the previous section come about because of the position-based control of the forming roller. The desired shape of the product can be obtained by fitting the material tightly to the mandrel. This can be accomplished by pressing the material onto the mandrel with an appropriate force, instead of leaving the clearance between the mandrel and the roller equal to the wall thickness. Hence we investigated the feasibility of force feedback control for metal spinning.

Hybrid position/force control [7] was applied in this study. As for the feeding direction X parallel to the mandrel surface, the forming roller was position-controlled in a constant velocity $\dot{X}_d$. The pushing force F_Y of the roller normal to the mandrel was controlled to be a constant value F_{Yd}. PD feedback and PI feedback were adopted for the position control and the force control, respectively. The control law is represented as,

$$\boldsymbol{f} = \begin{bmatrix} f_x \\ f_y \end{bmatrix} = \boldsymbol{f}_P + \boldsymbol{f}_F \qquad (2)$$

$$\boldsymbol{f}_P = \boldsymbol{M}\boldsymbol{J}^{-1} \begin{bmatrix} k_{vX}(\dot{X}_d - \dot{X}) + k_{pX}(X_d - X) \\ 0 \end{bmatrix}$$

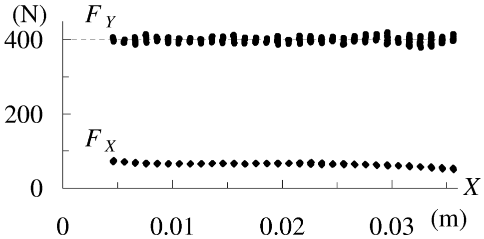

Fig. 16: Forming force

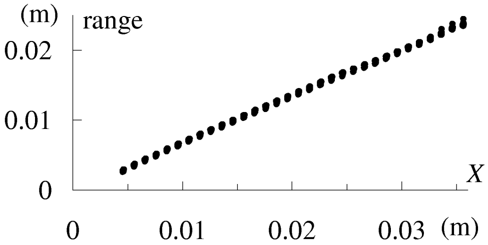

Fig. 17: Height of flange

$$\boldsymbol{f}_F = \boldsymbol{J}^T \begin{bmatrix} 0 \\ F_{Yd} + k_{pF}(F_{Yd} - F_Y) + k_{iF}\int (F_{Yd} - F_Y) \end{bmatrix}$$

where f_x, f_y are the force of the x and y axes, $\boldsymbol{M}$ is an inertia matrix, $\boldsymbol{J}$ is a Jacobian matrix of XY frame with regard to xy frame, and k_{vX}, k_{pX}, k_{pF} and k_{iF} are feedback gains.

This control law (2) was employed for the shear spinning experiment. The feeding velocity $\dot{X}$ was 0.1 mm/s and the mandrel rotation $\dot{\theta}$ was 60 rpm, as in the previous section. The pushing force F_Y of the roller was controlled to 400N, based on the pushing force with 0.25 mm clearance, which led to a good result in the experiments of the previous section. At first, xy-position control was applied until the roller contacted the blank and the material was dented following the edge of the roller. Then the control was switched to the hybrid position/force control and the forming conducted.

Figure 16 shows the forming force F_X and F_Y. The pushing force F_Y of the roller was maintained about the desired value by the feedback control. **Figure 17** shows the height of the flange. The forming was achieved without generation of wrinkles. **Figure 18** shows an example of the finished product using this control method. The wall thickness was 0.56 mm to 0.57 mm, which almost agreed with the theoretical value of Eq. (1)

This method frees metal spinning from the setting of the clearance between the mandrel and roller. Fine positioning of the roller relative to the mandrel is unnecessary. The same value of the pushing force can be used regardless of the stiffness of the machinery. In addition, this method is effective not only for shear spinning but also for final phase of multi-pass conventional spinning when the material is forced onto the mandrel.

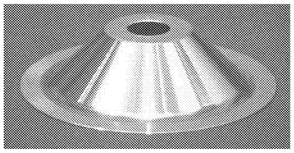

Fig. 18: Product by force control

6 Conclusions

We presented our study on metal spinning using robot control technology. First we discussed the background and purpose of the study. The experimental setup and preliminary experiments were described. In addition, we considered the effect of the clearance between the mandrel and the roller. We proposed metal spinning using hybrid position/force control, and verified its effectiveness experimentally.

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