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Synchronous multipass spinning of oblique-bottom shape☆

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ABSTRACT

Recently, various methods for the metal spinning of noncircular shapes have been proposed to overcome the limitation of its application range. In this study, a metal spinning method for noncircular shapes with oblique bottoms is proposed. This method is a combination of synchronous spinning and multipass spinning, in which the roller is synchronized with the mandrel rotation to track a noncircular cross section while the workpiece is gradually deformed without much thinning through some paths of the roller. The roller trajectory is calculated by linear interpolation in the radial direction and axial direction between the inclined blank shape and the inclined cross section of the product. A circular cup and square cup with an oblique bottom and vertical side walls are successfully spun using this method. As the wall thickness locally increases at the side edges of the square cup, the thickness distribution is equalized by using an intermediate circular shape. This method interpolates the roller trajectory between the blank shape and intermediate shape and between the intermediate shape and the product. The difference in the wall thickness is reduced since the square shape is formed via a cylindrical shape. In addition, the effect of the process parameters on the forming results is experimentally investigated.

1. Introduction

Metal Spinning is a plastic forming method for circular shapes in which a roller is pressed against a metal sheet or metal tube rotating on a lathe. It is widely used as a method of manufacturing round metal parts and products, such as automobile parts, aerospace parts, pressure vessels, liquid containers, funnels, nozzles, and parabolic antennas. Compared with stamping or deep drawing, it is more suitable for high-mix low-volume production because of its low tooling cost.

The recent development of metal spinning methods has also enabled the forming of various noncircular shapes to overcome the limitation of the application range of metal spinning. These new methods are generally classified into two types: synchronous spinning and force-controlled spinning. In synchronous spinning, the radial displacement of the roller actively synchronizes with the rotation angle of the workpiece. The forming roller moves in the radial direction in accordance with the rotation angle of the workpiece so that the trajectory of the contact point between the roller and the workpiece becomes the target cross-section shape. The sectional shape is changed along the axial direction and the whole workpiece is formed into the target shape.

Amano and Tamura (1984) formed an elliptic cone from an aluminum sheet by moving a forming roller mechanically synchronized with the rotation of a spindle and pushing the material onto an elliptic mandrel. A mechanical cam, gears, and a lever were used to drive the roller. Xia et al. (2010) also used gears and a three-dimensional cam in a method called “profile driving” to fit the motion of a forming roller to the mandrel shape, and formed cone shapes with noncircular cross sections.

Shimizu (2010) adopted the numerical control of stepping motors to move a roller in synchronous spinning and formed elliptic and square cones from aluminum sheets. Arai et al. (2005) conducted noncircular tube necking of elliptic and eccentric cross sections by synchronous spinning using a CNC spinning machine with a spindle axis driven by a servo motor. The use of computer control in driving the forming roller and the spindle rotation makes complicated mechanisms for the synchronization of the roller and spindle unnecessary. It reduces the cost of the dedicated cam for each cross- section shape and can make the noncircular spinning process more flexible.

Another type of noncircular spinning is force-controlled spinning, in which a noncircular mandrel is used and the pushing force of a roller is controlled so that the material is pushed onto the mandrel. As the mandrel rotates, the roller follows the cross-section shape of the mandrel to maintain an appropriate pushing force. Awiszus and Meyer (2005) used two rollers that pulled each other by strong springs, which

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pinched the workpiece and the noncircular mandrel. A semi-triangle cone was formed from a steel sheet by this method. Arai (2005) applied force-feedback control for noncircular metal spinning. A force/torque sensor was attached at the base of the forming roller and the pushing force was fed back to a computer to control servo motors so as to keep the pushing force constant. Arai (2006) used linear servo motors to drive a roller to realize faster motion of the roller and reduced the forming time of noncircular shapes.

The previous methods described above except for that of Arai et al. (2005) spun the target shape from a sheet blank with just one pass of the roller along the mandrel surface, and consequently they are classified into shear spinning or simple conventional spinning. Shear spinning reduces the wall thickness from the original thickness of the blank, while the outer diameter of the blank does not change during the forming. The wall thickness t of the product is

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

where the thickness of the blank is t_0 and the half cone angle is α. This relation is called the “sine law”. When the half cone angle is zero, i.e., in the case of a vertical wall, the wall thickness after forming becomes zero from Eq. (1) and fracture occurs. Therefore, a product with vertical walls cannot be formed by shear spinning from a metal sheet.

In contrast, the multipass (conventional) spinning process for circular shapes presses a metal sheet onto a mandrel with multiple tool paths. A forming roller moves back and forth between the mandrel surface and the periphery of the workpiece. The blank gradually deforms closer to the mandrel shape with less thinning of the side wall than that predicted by the sine law. Simple conventional spinning is a special case when a single path is used, but it only allows a shallow shape when the diameter of the blank is close to that of the mandrel.

Multipass spinning has been expanded to noncircular shapes in some studies. Härtel and Laue (2016) formed a tripod shape via two roller paths and optimized the forming conditions on the basis of FEM simulation. A circular cone was spun as a preformed shape from a flat blank in the first path, and then a roller pushed the workpiece into the final shape of the tripod mandrel, which was difficult to spin with a single pass owing to wrinkling. Sugita and Arai (2015) proposed synchronous multipass spinning to spin noncircular shapes with vertical walls such as a square cup (Fig. 1). Synchronous multipass spinning is a combination of multipass spinning, which progressively performs forming from a flat blank in multiple steps, and synchronous spinning, which controls the roller displacement in the radial direction by synchronizing with workpiece rotation angle. Although the three-dimensional tool trajectory of multiple paths appears to be rather complicated, it can be easily calculated from the mandrel shape, the blank shape, and the normalized path profile. Music and Allwood (2011) found that the contact force between the workpiece and mandrel in multipass spinning is locally distributed in only several small areas. On the basis of this result, a spinning machine for noncircular shapes was developed that supports the workpiece using three movable rollers instead of the mandrel.

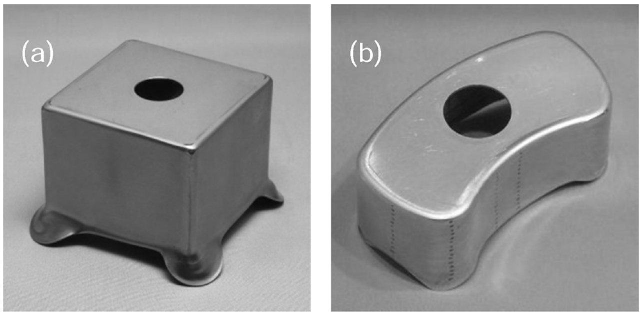

Fig. 1. Photographs of noncircular shapes with vertical walls formed by synchronous multipass spinning.
(a) square cup, cold-rolled steel (Arai, 2013).
(b) concave cross section, aluminum (Sugita and Arai, 2011).

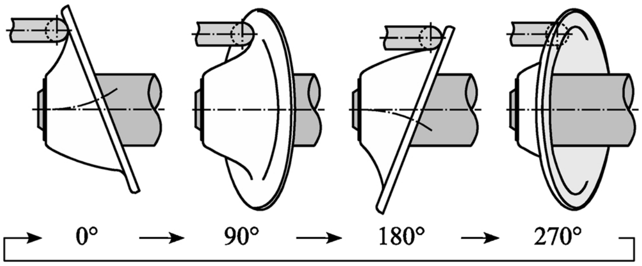

Fig. 2. Oblique synchronous spinning performed by Sekiguchi and Arai (2010).

From a different viewpoint, all the methods described above deal with non-oblique spinning. The cross section being formed is always perpendicular to the spindle axis. In contrast, several spinning methods were developed to form inclined and curbed shapes. Irie (2001) developed a spinning machine for the tube necking of oblique shapes. Planetary rollers driven by a spindle rotate around the workpiece and change the rotating radius so as to neck the tube end, while the workpiece is rotated relative to the spindle axis to obtain an oblique end. Xia et al. (2012) simulated the forming process of this method and investigated the effect of various forming parameters. Sekiguchi and Arai (2010) carried out oblique synchronous spinning of a metal sheet. This method expands the synchronous spinning method to enable the forming of oblique and curved shell shapes. The roller motion in the axial direction as well as that in the radial direction synchronizes with the workpiece rotation (Fig. 2). The curved shape is defined by continuously changing the inclination angle of the cross section. As this method is a type of shear spinning, shapes with vertical walls cannot be formed owing to the sine law.

This paper deals with target cup shapes that simultaneously have i) a noncircular cross section, ii) an oblique bottom and iii) vertical side walls. These shapes cannot be formed from a sheet blank by the previous methods reviewed above. Three types of roller motion, i) radial motion synchronized with the spindle rotation to follow the noncircular cross section, ii) axial motion synchronized with the spindle rotation to follow the oblique bottom and blank and iii) step-by-step tool paths that change a flat blank to vertical walls, should be unified to a tool trajectory to achieve each feature of the target shape. For this purpose, the synchronous multipass spinning method in Sugita and Arai (2015) is extended to afford synchronous motion in the axial direction.

Section 2 describes how to calculate the tool trajectory in this method. Section 3 describes forming experiments on circular and square cup shapes with an oblique bottom. Section 4 presents the forming method via an intermediate shape to avoid material concentration at the corners of the square cup. Section 5 experimentally shows the effect of the process parameters on the forming result. Section 6 summarizes the findings obtained in this study.

2. Method for calculation of tool trajectory

2.1. Tool trajectory in synchronous multipass spinning

Before explaining oblique synchronous multipass spinning, the tool trajectory calculation for synchronous multipass spinning in Sugita and Arai (2015) is reviewed here. In the spinning of a noncircular shape, the movement of the roller is represented by three-dimensional data in the axial direction and the radial direction and the rotation angle of the workpiece. A three-dimensional tool trajectory should be planned from the initial flat blank to the final shape of the product.

To closely fit the material onto the mandrel in the final state, the tool trajectory should move along the completed shape of the product. In the initial state, the tool trajectory should move along the blank