New spinning technology for producing square section die-less spun parts in the sheet metal forming process

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Abstract  Sheet metal spinning is one of the main forming processes, being characterized by flexibility, low cost, reduced manufacturing time, and high formability. Where a flat metal blank is rotated at a high speed and this spun part is formed by pressing a forming tool into the blank, however, this process is limited to axisymmetric parts. This research thus aimed to design and build a simple and flexible mechanism for producing asymmetrical spun parts to allow non-circular forms (polygons) to be formed without interrupting the rotation of the turned blank, being synchronized with the rotation of the special forming tool. The proposed mechanism is based on developing a synchronous spinning machine in which the rotational motion and traditional lathe machine feed are monitored to maintain synchronization with the tool rollers (special forming tool), where the latter controlled by electric motors. The speed of the electric motors is controlled by a variable frequency drive (VFD), pulse-controls and specialized software. The proposed machine can be applied to multiple product shapes by changing the pulse-control in the software code, making the machine much more flexible than other options. Square cross-section parts were formed by cutting aluminum alloy sheets (1050) into a circular shape of 1.5 mm in thickness and 150 mm diameter. The experimental study then examined the effects of various process parameters on the spinning process, spindle speed of the lathe, feed ratio, and forming tool diameter. Three values were adopted for the three parameters, spindle speeds of 48, 68, and 135 RPM, feed ratios of 0.16, 0.22 and 0.32 mm/rev, and forming tool ball diameters of 16, 22, and 25 mm. The results showed that the maximum average in wall thickness reduction was about 27.44 %, and the maximum average error in dimensional accuracy was 6.47 % for spun parts made with a 45 mm mandrel.

1. Introduction

In spinning processes, a metal sheet (workpiece) is generally supported on a rotating mandrel, while a tool is used to deform the workpiece over the mandrel, this means that only products with an axisymmetric shape can be obtained. Die-less spinning has been increasingly popular in the manufacturing field, based on its advantages of low cost and high flexibility [1], however, and in recent years, novel spinning processes have been developed to challenge the limitations of traditional spinning, with new technologies used to manufacture axisymmetric, circular cross-section, and uniform wall-thickness parts.

An overview of the most important research published in this field includes the work of Russo et al [2], presented a robust methodology for an asymmetric mandrel-free spinning technique and demonstrated its successful application to spin circular, elliptical, and square parts with no dedicated
tooling. They reported that the range of curvature in the target part’s contours could be used to quantify its degree of asymmetry, as well as investigating the influence of this parameter on the formability of spun parts in a series of experimental trials. Zhen Jia et al [3] investigated a die-less process to achieve cone-shaped square section parts using a five-axis Computerized Numerical Control (CNC) spinning machine, adopting a roller path designed and adjusted to calculate the degree of the edge arc of the square section parts. This methodology was used to form a square section die-less part, and the roller was caused to move forward and backward in the radial direction, accompanied by a rotation of the workpiece and its simultaneous procession along the axial direction. Sugitaa et al [4] formed asymmetric shapes with circular cups and rectangular boxes using synchronous multi-pass spinning with rotational pass sets, with the roller path calculated by linear interpolation between the mandrel and the blank along each pass set. Shimizu [5] also developed an asynchronous spinning machine to overcome the limitations of conventional axisymmetric spinning, the motion and feed of the mandrel and the roller feed were synchronized using pulse control to obtain an asymmetric truncated elliptical-cone-shaped product. The roller path was generated using control software, taking into account the errors caused by the step pulse control, and thus asymmetric sheet metal forming was successfully carried out a synchronous spinning method.

This research aimed to design and build a simple and flexible mechanism based on a combination of mechanical and electronic systems to achieve an asymmetric forming process, such as forming a polygonal shape (square section) with spun parts without using a specific mandrel.

2. Theory

The concept of forming a rectangular spun part by spinning process based on the rotation of a blank with the aid of a forming tool that has a parallel axis of rotation with synchronised speeds during the machining process, is clear. The forming tool speed may be the same or multiple spindle speeds depending on the desired shape. A kinematic diagram of the process for a rectangular shape is presented in figure 1.
Figure 1. Kinematic step diagram of an asymmetric spinning process for rectangular polygonal shape.
2.1 Determine where two circles intersect
The paths for both the forming tool and the blank are circular and intersect in a specific zone to generate a straight edge. To determine length of the part edge, a method for determining the intersection of two circles is used, as shown in figure 2. Here, two circles with radii \( r_0 \) and \( r_1 \), where points \( p_0, p_1, p_2, \) and \( p_3 \) have coordinates \((x_0, y_0)\), and so forth. Hence

\[
d = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2}
\]  

(1)

where \( d \) = the distance between centers of the two circles.

From Pythagorean Theorem,

\[
h^2 = r_0^2 - a^2 = r_1^2 - b^2
\]

(2)

Substituting \( a = d - b \) and multiplying,

\[
r_0^2 - d^2 \cdot d \cdot b - b^2 = r_1^2 - b^2
\]

(3)

\[
\therefore b = \frac{r_1^2 - r_0^2 + d^2}{2 \cdot d}
\]

(4)

Similarly,

\[
a = \frac{r_0^2 - r_1^2 + d^2}{2 \cdot d}
\]

(5)

All of these values are known, allowing the solution for \( a \) and \( b \) for equation (4) and equation (5), those distances are he used to find the \( p_3 \).

The \( x \) and \( y \) coordinates for point \( p_3 \) are,
\[ x_3 = x_2 \pm \frac{h(y_1 - y_0)}{d}, \quad y_3 = y_2 \pm \frac{h(x_1 - x_0)}{d} \]  

(6)

From equation (6), the length of polygon edge can be calculated as

\[ l = \sqrt{(x_3(1) - x_3(0))^2 + (y_3(1) - y_3(0))^2} \]  

(7)

where \( l \) is the length of line of intersection between the two circles. This length was used to design the parts, as shown in figure 3.

**Figure 3.** The rectangular shape of a spun part where the length of edge is calculated using equation (7).

The shape of the polygonal spun part manufactured is related to the ratio of the rotary speed of the forming tool to the spindle speed and the number of chosen edges on the spun part. The relationship between these factors is expressed by the following equation [12],

\[ E = z_t \times \frac{n_{tool}}{n_{spindle}} \]  

(8)

where \( E \) stands for the number of flat edge surfaces, \( z_t \) is the number of balls in the forming tool, and \( n_{tool} \) and \( n_{spindle} \) are respectively the rotary speed of the forming tool and spindle speed.

Assuming constant ratio of speed,

\[ \beta = \frac{n_{tool}}{n_{spindle}} \]  

(9)

where, \( \beta \) speed ratio.
To generate a regular polygon on the blank with $E$ sides, the speed of the spun part (spindle speed) and the tool ratio must equal the ratio between the number of edges in the polygon’s spun part $z_p$ and number of balls in the forming tool $z_t$.

$$\beta = \frac{n_{tool}}{n_{spindle}} = \frac{\omega_{tool}}{\omega_{spindle}} = \frac{z_E}{z_t}$$

where $(\omega_{tool})$ and $(\omega_{spindle})$ are the angular velocities of the forming tool and spindle, respectively.

For a rectangular spun part, the number of sides is four; in this case, the number of balls in forming tool was chosen to be two (one, two, or four balls may be used in the forming tool), thus from equation (8),

$$E = z_t * \frac{n_{tool}}{n_{spindle}}$$

$$4 = 2 * \beta \quad (12)$$

$$\beta = 2 \quad (13)$$

So the angular velocity of forming tool should be double the angular velocity of the spindle.

3. EXPERIMENTAL SETUP

This section discusses the experimental work, adopted design, and mechanical system used to achieve an asymmetrical part using a spinning sheet metal forming process. It thus describes the process stages used to product the final part.

3.1 Designing a mechanical system for the spinning forming Process

In this study, a mechanical system was designed and built to achieve the rotational action of a forming tool and to automate the sliding movements of the lathe carriage in both the Z and X direction.

The set-up of the mechanical system is very simple, and the forming equipment was installed on the lathe machine carriage as listed below:

A- Part one: the mechanical system of rotational action of forming tool.
1. Frame.
2. Three-phase induction Motor (2.2KW or 3Hp).
3. Worm gearbox reducer.
4. Forming tool.
5. Sprockets and chain.

B- Part two: The mechanical system for axial movements of the lathe carriage.
- Three-phase induction motor with gear box built-in (0.75KW or 1Hp).

Figure 4 illustrates the mechanical system for the forming tool.
3.2.1 Disk holder.
The disk holder is a circular disk made from cast iron with a special design. The main function for the holder is carrying the ball tool as inserted into the cutting tool holder. The disk holder has seven holes in its edge, four of which have 90-degree pitch angle make rectangle shapes and three of which are spaced with 120-degree pitch angles, making a triangle shape. These shapes are shown in dotted lines in figure 5.

3.2.2 Ball tool.
The ball tool was designed and made by gathering readily available parts. The first was a ball bearing, characterized by very high hardness, with three diameters chosen for the experimental work (16, 22,
and 25 mm), the second was the screw, characterized by M10*1.25. The head of the bolt screw was drilled with a cone shape using a lathe to create a cavity for the ball, giving a better solution for the fitting of the ball in the center of rotation in the bolt screw. The bolt with cone cavity and 22 mm ball is shown in figure 6.

![Figure 5. Design of disk holder with dotted lines for shapes.](image)

**Figure 5.** Design of disk holder with dotted lines for shapes.

![Figure 6. Bolt screw with cone cavity and 22 mm ball.](image)

**Figure 6.** Bolt screw with cone cavity and 22 mm ball.

### 3.2.3 Ball tool and disk holder.

The ball tool was inserted in the disk holder to make the forming tool, with the ball and screw joined together using arc welding and the disk holder fastened as shown in Figure 7.

![Figure 7. Forming tool after assembling:](image)

**Figure 7.** Forming tool after assembling:
- a-Forming tool with four ball, b- forming tool with three balls

### 3.3 Enhanced spinning operation (moving mandrel)

The aim of using a moving mandrel was to create a backup load on the blank (pre-loading) during the spinning process. In this process, the moving mandrel slides axially on a clamping shaft fixed in the spindle chuck, with a back-up spring in the climbing shaft behind the moving mandrel. This method provides a backup force mimicking the two-point forming process used in incremental sheet metal forming.
The climbing shaft was made of medium carbon steel of 45 mm diameter and 1 m length, and the moving mandrel was made from Teflon with 26 mm and 250 mm inner and outer diameters, respectively. Figure 8 shows the moving mandrel and figure 9 shows the actual parts used in the enhanced spinning operation. The mechanical system for the rotation of the forming tool is illustrated in figure 9.

Figure 8. The movement mandrel.

Figure 9. The enhanced spinning tool after grouping: moving mandrel, spring, and clamping shaft.

4. Producing the spun part square shape
A rectangular spun part made of Aluminum alloy 1050 was produced from a circular blank with an outer diameter of 120 mm. A wide range of alternate parameters are possible though, as illustrated in Figures 10, 11, and 12, which show the steps for making various types of rectangular spun parts. Figure 10 shows the steps for making rectangular parts by using a 45 mm clamping shaft and tools fixed directly to the spindle of the lathe and forming tools rotating in the same direction, Figure 11 show the steps for making rectangular parts by using 75 mm clamping shaft with blanks and tools moving in the same direction of rotation, and Figure 12 show the steps for making rectangular parts using a 75 mm clamping shaft moving so that there is an opposite direction of rotation between the blank and forming tool.

Figure 10, show steps for made rectangular parts by using 45mm clamping shaft.
Figure 11 show steps for made rectangular parts by using 75mm clamping shaft.
Figure 11. Making rectangular parts using a 75mm clamping shaft: A) Produce part; B) Depth increase; C) More depth; D) Final part.
In Figure 12, the images from A to C show a reduction in twisting drift such that image D exhibits no twisting drift.

Figure 12. Making rectangular parts using a 75mm clamping shaft with opposite directions of rotation: Produce part with high twisting drift; Twisting drift decrease; Reduced twisting drift; D) Final part with no twisting drift.
5. CONCLUSIONS

In this survey, an experimental investigation with simulation was carried out to create rectangular shaped spun parts by adding synchronized speed rotation to the forming tool to match the spindle speed of the lathe. The conclusions of this work are summarized in the following points:

1. Based on the simulation of movement for both tools and spun part as illustrated in figure 1, when the number of the balls in the forming tool is four, a square shape will fail, as the straight edge is destroyed where a ball hits the spun part in the edge zone corner; such a smash is not seen with a tool with two balls at double the tool speed, however.

2. Based on the practical investigation, as shown in figures 10 and 11, the larger the diameter (75 mm) the better the results with regard to obtaining straight surfaces and edges on the spun part, as when the diameter of the spun part increases to give a small difference value as compared to the tool diameter, the intersection of blank and tool is improved, and thus the straight edge is improved.

3. The surface changes from flat to concave when the tool rotation is in the opposite direction to the blank rotation; however, the result is still a square shape.

4. The main parameter affecting the formation of a square shape is the spindle speed: low speed gives a better straight surface and edge than high speed, with the latter promoting spiral waves on the surface.

5. The condition for success in this process is that the speed of tool should be both constant and synchronized with the blank speed; a small angular deflection error is, however, likely to occur in spun part where the straight surface deflects at an angle.

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