The research on axial force of manufacturing metal bellows using water jet incremental forming technology

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Abstract—Metal bellows have been widely used as expansion joints to absorb expansions and contractions in many engineering applications from the start of the century. In conventional metal bellows forming process, the main disadvantages are high cost of tooling required and lack of flexibility. To avoid the disadvantage, this study presents a new metal bellows forming process using water jet incremental forming technology. In this paper, the incremental forming method of high-pressure water jet is used to study the forming technology of bellows.

1. Introduction

High pressure water jet incremental sheet metal forming (WJISMF) is a new type of sheet metal forming technology. This technology originated from the idea of "layered manufacturing" of rapid prototyping that is the formed part is segmented into a series of two-dimensional cross-sectional layers along its height direction. When water jet impacts on the sheet metal, local plastic deformation is produced. Complex shell parts are manufactured due to continuous local plastic deformation. This technology is a kind of green forming process because of low friction and no need of lubrication.

Metal bellows have been widely used as expansion joints to absorb expansions and contractions in many engineering applications from the start of the century.

The processing methods of metal bellows mainly include: hydraulic forming [1], rigid die bulging [2], rolling forming [3], welding forming [4], superplastic forming [5] and electromagnetic forming [6].

In conventional metal bellows forming process, the main disadvantages are high cost of tooling required and lack of flexibility. To avoid the disadvantage, this paper presents a new metal bellows forming process using water jet incremental forming technology.

Many scholars have studied incremental forming, but they all focus on the forming of disc parts. Due to the limitation of traditional incremental forming process, bellows cannot be processed by ordinary incremental forming. In this paper, the metal bellows forming is studied on the developed five axis NC high-pressure water jet incremental forming machine tool. According to the existing research results, the process parameters of progressive forming disc parts include: target distance (the distance from the nozzle to the part), layer distance (the falling distance of the nozzle between each layer), nozzle diameter and so on. However, the forming limit of metal bellows is very large. In order to improve the reliability
of forming, an axial force needs to be added.

2. Introduction of manufacturing metal bellows using water jet incremental forming technology
High-pressure water jet incremental forming uses the pressure of water to form the desired bellows. The principle is that the tubular part is fixed to the forming machine tool, the high-pressure water is hit on the pipe wall of the part, and the workpiece or nozzle rotates around the axis line of the workpiece. At the same time, an axial pressure is applied to the blank, and the formed bellows is obtained under the action of the high-pressure water jet. The forming schematic diagram is shown in Figure 1. Firstly, place the rotating L-shaped nozzle inside the workpiece and make the rotation center line of the nozzle coincide with the center line of the pipe blank. At the same time, the nozzle has reciprocating motion along the axis of the workpiece (as shown in Figure 1a). After the nozzle rotates for one week, the nozzle moves a certain distance along the axial direction of the workpiece, and the prototype of the part is processed according to the size requirements of the bellows. The axial force is applied to the section of the bellows to be formed. Then, the above repeated actions are carried out to finally process a ripple. In this way, multiple corrugations are processed repeatedly to form the desired bellows.

3. Effect of axial pressure on bellows forming
It is assumed that in the high-pressure water jet incremental forming process, there is only pure shear deformation along the vertical height direction. The material deformation diagram is shown in Fig. 2. Assuming that there is only plane shear deformation at the moment of water column acting on the sheet in water jet incremental forming, the radial position of any point in the sheet remains unchanged before and after deformation. The material flows only in the axial direction, the sheet deformation can be regarded as pure shear deformation.

Fig.1 The forming schematic diagram

Fig.2 The material deformation diagram
According to the law that the volume remains unchanged before and after metal plastic forming, the thickness change formula before and after sheet metal forming can be obtained, namely

$$t_0 \cdot dx = t \cdot s$$

$$dx = s \cdot \sin \alpha$$

$$t_0 \cdot s \cdot \sin \alpha = t \cdot s$$

$$t = t_0 \cdot \sin \alpha$$

$$\tan g \alpha = \frac{d_1 - d_2}{h}$$

where:
- $t_0$—Sheet thickness before forming (mm);
- $t$—Sheet thickness after forming (mm);
- $\alpha$—Forming half cone angle (°);
- $d_1$—Large diameter radius of formed cone (mm);
- $d_2$—Small diameter radius of formed cone (mm);
- $h$—Height of forming cone (mm)

Equation (4) is a basic law followed by the change of sheet thickness in water jet progressive forming under ideal conditions—Sine law. According to the above sine law, the smaller the half cone angle, the thinner the sheet thickness $t$ after forming, and the easier it is to crack. The larger the half cone angle, the thicker the sheet thickness after forming, and the less likely it is to crack. The half cone angle when the material just breaks is called the limit half cone angle. Therefore, for single pass incremental forming, in order to avoid the fracture of deformation zone during forming, the half cone angle must be greater than the limit half cone angle.

According to formula 4, reducing the height of the formed cone can increase the half cone angle $\alpha$, the method to reduce the forming height is to increase the axial force $F$ at both ends of the workpiece blank during workpiece forming. Increasing the axial force can reduce the forming height and improve the sheet forming limit.

However, the axial force has a limit value. Too much axial force will cause the instability of bellows. Aleksander K. [7] studies the stress–strain state of a U-shaped expansion bellows under an internal-pressure induced load. The simplified model of bellows is shown in Figure 3. They calculated the following formula for the axial force of the bellows.

$$F = p \pi D_{eq}^2 / 4$$

$$D_{eq}^2 \approx (D_1^2 + D_2^2) / 2$$

where:
- $F$—axial force of the bellows(N);
- $p$—internal pressure(pa);
- $D_{eq}$—inner diameter of bellows(mm);
- $D_1$—outer diameter of bellows(mm);
4. Experimental development

4.1. Fixture manufacturing

According to the analysis of the forming characteristics and processing path of bellows, the bellows fixture is designed in this experiment. The water jet incremental forming of bellows is mainly divided into two steps. The first step is to form the cone. First, use the nozzle of high-pressure water jet for one-time forming to preliminarily form the cone shape. The second step is multi-channel forming to fine form the rough formed cone respectively. In the second step, an axial pressure needs to be applied, which will be introduced respectively below.

The fixture model used in the first step of rough forming is shown in Figure 4, which is mainly composed of guide shaft, compression nut, spring, upper fixture ring assembly, lower fixture ring assembly and fixture base. Its physical diagram is shown in figure 4b), in which the upper clamp ring assembly is shown in Figure 4c) and the lower clamp ring assembly is shown in figure 4d). The periphery of the upper and lower circles of the formed blank pipe is respectively installed between the inner ring and the middle ring in the upper and lower clamping ring components, and is clamped by bolts and wedges. The purpose of setting the middle ring is to adapt to the processing of pipes with different specifications and sizes. When forming, the L-shaped nozzle is used to act the high-pressure water jet on the inner wall of the pipe to form each section of cone.

The fixture used in the second step of fine forming is shown in Figure 5, which is mainly composed of compression nut and guide shaft. It is composed of compression spring, outer clamping ring assembly, lower clamping ring assembly and fixture base. The photo of fixture is shown in figure 5b). During forming, two identical outer clamping ring assemblies are used to clamp the upper and lower sides of a section of ripple to be finished, and the water jet acts on the inner wall of this section of ripple to form the ripple. The function of the four springs in the fixture is to exert axial pressure on the forming of the bellows.
4.2. Experimental verification

In order to give full play to the plastic deformation ability of the material, the welded pipe with wall thickness of 0.3mm and diameter of 220mm is selected as the workpiece for manufacturing bellows. The process parameters of metal bellows manufactured by water jet incremental forming technology are selected as shown in Table 1.

According to the analysis of several experimental results, the loading curve of axial force should gradually increase with the increase of time. When the initial applied force is greater than 160n, the processed bellows will wrinkle. The loading curve is shown in Fig. 6. Fig. 7 is a photo of manufactured parts.

| Process parameter name | Nozzle rotation speed (r/min) | Nozzle diameter (mm) | Distance between nozzle and workpiece (mm) |
|------------------------|-------------------------------|----------------------|------------------------------------------|
| Selected value         | 60                            | 1.2                  | 10                                       |

Fig.6 The loading curve

Fig.7 Photo of manufactured parts
5. Conclusion
High-pressure water jet sheet metal forming is a new incremental forming method. ISEKI h of Japan has made a preliminary study on the forming mechanism of water jet sheet metal forming; So far, scholars from various countries have conducted a small amount of research on it. The research results show that compared with the traditional forming method, this forming method has the advantages of no die or half die processing, saving die cost and shortening production preparation cycle.

In this paper, a large number of experimental studies on the incremental forming of metal bellows are carried out and analyzed. Through theoretical research and experimental verification, the following conclusions are drawn.

1) The reason why the axial force needs to be increased in the processing of bellows is analyzed. According to the research of other scholars, there is a limit value of axial force in bellows processing.
2) Aiming at the forming of bellows parts whose forming angle is less than the forming limit angle, a better processing path of progressive forming of corrugated pipe with high-pressure water jet flow is proposed. This path can form bellows with good quality through a large number of experiments.

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