Precision Machining and Nondestructive Evaluation for Tiny Arc of a Valve Body

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Abstract. The valve body is one of the key parts in the solenoid valve products, which mainly plays the role of seal. Due to the airtight index, the tiny arc structures of the valve port are complicated, which causes the high requirements of dimensional accuracy, geometric tolerance and the surface roughness of the product and difficulty of machining and inspection. Traditional processing method can not meet the demand of batch and rapid production. This paper presented a new method of precision machining and inspection for tiny arc, which realized the precision machining and nondestructive evaluation of Ra0.2 roughness and R0.2mm arc surfaces of valve bodies with GYJ130 soft magnetic alloys. The processing methods greatly reduced the requirements for the skill level of operators. The experimental results showed that the machining efficiency of valve body was increased at least three times, and the qualified rate was increased from 60-70% to more than 96%, while the cost of production and material were reduced proportionally.

Keywords: Tiny arc; Magnetically soft alloy; Precision machining; Rapid fabrication; Nondestructive evaluation.

1. Introduction

The valve body is one of the key parts of the valve, which is utilized for seal. The tiny arc structure for seal at the valve port is complex. It is difficult to manufacture and measure the high dimensional accuracy, geometric tolerance and surface roughness of the product. Furthermore, most valve bodies are made of GYJ130 soft magnetic alloy, its poor processing performance makes more difficulties for selecting tool material and tool geometric parameter [1].

In the traditional processing method, it is common to machine one sample before each batch of product goes into production. In the trial cutting processes, the forming tools are used to machine the bottom of valve ports and the process parameters are confirmed. Then the solidified process is utilized to the formal valve port, so that the tiny arc at the seal structure is manufactured once. This machining method mainly depends on the accuracy of the circular arc profile of the tool edge to ensure the profile accuracy and surface quality of the seal structure, while the grinding of the tool edge completely depends on the technical level and experience of operators. Therefore, the products processed by this method have poor quality stability and low processing efficiency.

Meanwhile, due to the R0.2mm arc structure of at the valve ports, it is difficult to measure directly the relevant dimensions of the valve ports by conventional inspection means. So it is necessary to split the parts into sections use slow-feeding wire-cut machine, and take points under the omnipotence tool-microscope to detect the geometric tolerance of each arc section. This method often causes low inspection accuracy and is interfaced by external factors, which is easy to cause batch waste and qualified workpieces waste due to the lost opportunity to find unqualified products.
2. Research on Innovative Processing Methods and Measuring Techniques

2.1. Analysis of Machining Process for Tiny Arc of a Valve Body

The typical seal structures of some valve body are shown in figure 1.

![Figure 1. Typical seal structures of value body.](image)

As can be seen from the figures above, the typical seal structure of valve body has four characteristics like this:

1. The seal structure of valve body is generally a tiny arc of small size, the minimum up to R0.2mm;
2. The profile is a special curve structure, which can not be processed by the conventional cutting tools, which requires manual edge grinding molding tool and high technical level of the processors;
3. Conventional measuring tools and methods are unable to check the size and shape of such structures;
4. The surface roughness of the structure is relatively high, which is basically between Ra0.2 and Ra0.8.

2.2. Selection of Tool and Parameter Modification

2.2.1. Selection of Tool Material

Due to the high adhesion and poor thermal conductivity of the soft magnetic alloy, it is very easy to aggravate tool wear because of the chip tumor generated during the turning process[1]. Therefore, the classical carbide turning tool is selected. To ensure the strength of the tool, the diamond grinding wheel is used to finish the angle of the tool for avoiding machining interference. Meanwhile, the surface roughness of workpiece can be improved greatly. This method can ensure a high efficiency of the tailor-made tool, and the tool sharpening does not need a very high level of skill. The operators of intermediate skill or above can complete it with strong operability and popularity.

2.2.2. Selection of Tool Parameter

For machining the surface of cylindrical parts, The change of the axial dimension increases with the increase of the tool nose arc radius[2]. Sealing circular arc has high requirements on the shape of arc curve, fullness and surface roughness, therefore, it requires one pass to be processed at the arc. The Φ1.2mm hole in the middle of seal structure in figure 1 restricted the tool feed. Through calculation, the auxiliary deviation Angle and the auxiliary back Angle of tool 1# should be transformed to 45°, as shown in figure 2 (a). In this way, the tool tip can penetrate into the small hole by 0.5mm, completely meeting the transition between the circular arc and the inner hole.
Meanwhile, in order to ensure the strength of the tool tip, the zero-degree front angle is adopted to remove a large number of materials in rough machining. To transform the cutter blade angle of tool 2# to 12°, as shown in figure 2 (b), so that the finishing of Φ1.2mm hole and R0.2mm arc can be completed in one continuous pass machining, implementation by numerical control program to ensure sealing circular arc curve shape, and the copying tool can be replaced by NC interpolation to ensure accuracy of model surface, it has solved well the machining difficulty of small circular arc, while the good geometric morphology of surface will largely determine the performance of valve [3].

2.2.3. Selection of Machining Parameters
If NC machining is carried out directly on the micro-line segment[4-5], the machining efficiency and quality will be reduced, which is because that the frequent change of acceleration causes machine vibration[6]. Based on that, a larger turning tool angle is adopted after the tool transformation. Machining parameters should be adopted in cutting process as shown in table 1.

Table 1. A typical cutting parameter.

| cutting speed (r/min) | amount of feed (m/min) | Depth of cut (mm) |
|-----------------------|------------------------|------------------|
| 1500                  | 0.05                   | 0.1              |

In the process of software programming, the trajectory of tool tip can be adjusted to ensure that the actual machining trajectory of tool tip conforms to the ideal trajectory. In the process of programming, the steps of sketching trajectory simulation and programming are strictly followed[7]. Therefore, in the finishing process, using tool 2# according to the cutter route coordinates point programming CNC machining program as shown in figure 3, and adjusting the cutter parameters by according to tool setting.

Figure 2. Cutting tools for tiny arc machining.
Figure 3. Arc processing route coordinate diagram (Seal structure in figure1 as an example).

2.2.4. Application Effect of Tool Modification

Through a lot of experiments to modify tool parameters, the technology method of machining the valve body seal structure curve by the standard tool combined with the NC program has been realized to complete the precision machining of the valve body small arc. The biggest advantage of this method is that replacing copying tool with NC interpolation to ensure accuracy of model surface, as well as judging the dimensional accuracy of the valve body seal structure by measuring tool outline dimensions and dimension data at the beginning and end of the CNC program on the product.

2.3. Optimized Measuring Method

2.3.1. Nondestructive Evaluation

Nondestructive evaluation refers to detect a few dimensions in the arc sealing surface to achieve the purpose of judging whether the whole sealing arc curve is qualified, through the conventional measurement method of three coordinates combined and the plug gauge without cutting valve body.

Inspection principle analysis: At present, valve body are processed on CNC lathe, turning tool tip radius R affects the machining accuracy of the parts. During the programming process, the path of the tool tip can be adjusted to ensure that the actual processing path of the tool tip is consistent with the ideal path, the tool tip trajectory can be converted to the ideal tool tip trajectory through calculation. In the actual machining process, the tool tip arc of the tool used should be checked in time, when calibrating the tool, you can use the tool compensation function of the CNC lathe system to optimize the size and fully consider the influence of the tool tip arc radius[8]. At the same time, the programming process strictly follows the sketch drawing trajectory simulation and programming steps, the method above can ensure that the processing route is the theoretical curve described by the mathematical equation in the CNC program. Therefore, it can be considered that by observing the tool
tip arc radius \( r \) and the product dimensional accuracy corresponding to the coordinate points in a numerical control program, it can be determined whether the actual machining curve of the program conforms to the theoretical trajectory, that is, the actual machining arc curve accuracy meets the design dimensional accuracy.

The arc sealing surface processing in figure 4 below is illustrated as an example. In the process of test method verification, the modified tool and machining parameters are used to process the test piece.

**Table 2. Application effect after tool improvement.**

| Project type       | Before                                      | After                                      |
|--------------------|---------------------------------------------|--------------------------------------------|
| tool               | Copying tools, line cutting or manufacturers customized tools after grinding transformation | Only the ordinary tool Angle modification, to avoid interference |
|                    | It is necessary to use whetstone to grind the cutting edge manually in the process of grinding transformation | When the tool Angle is transformed, use the ordinary grinding wheel to grind and keep sharp |
|                    | The time of single tool "transformation + manual sharpening" is about 2-3h | The time of single tool "transformation + tool sharpening" > is about 0.5-1h |

**Effect of processing**

| Effect of processing | Before                                      | After                                      |
|----------------------|---------------------------------------------|--------------------------------------------|
|                      | The accuracy of the tool arc profile is very high, and the surface roughness of the sealing arc profile can reach up to 1.6 after processing | The product arc surface precision is guaranteed by the numerical control program, does not depend on the tool precision, after processing the sealing arc surface roughness can generally reach 1.6 |
|                      | Due to the influence of tool precision, the seal structure arc precision can be controlled within 0.1, poor consistency | Numerical control system guarantees that the seal structure arc precision can be controlled within 0.01, high consistency |

**Skill levels**

| Skill levels                  | Before                                      | After                                      |
|-------------------------------|---------------------------------------------|--------------------------------------------|
| Senior technician or above    | Intermediate or senior worker or above      |                                            |

**Machining efficiency**

| Machining efficiency | Before                                      | After                                      |
|----------------------|---------------------------------------------|--------------------------------------------|
|                      | The processing time of each piece is 20min  | The processing time of each piece is 30min |
|                      | The polishing time of each piece is 20min   | The polishing time of each piece is 10min  |
|                      | An average of 2 polishing repairs are required | Qualified primary polishing               |

**Pass rate**

| Pass rate | Before                                      | After                                      |
|-----------|---------------------------------------------|--------------------------------------------|
|          | The pass rate of is 60~70%                  | The pass rate of is 96%                    |

**Processing economy**

| Processing economy | Before                                      | After                                      |
|--------------------|---------------------------------------------|--------------------------------------------|
|                    | A single cutting tool can be processed by a grinding about 3 products, at any time may be broken resulting in unrepairable products, leading to the waste of the previous processing procedures | A single tool sharpening can process about 30 pieces of products, in the process only need to check the tool sharp Angle no damage, whether the blade is sharp |
|                    | Production backup is 30%                    | Production backup is 10%                   |

**Figure 4. Sealing surface processing technology test piece.**

According to the mathematical model:

\[
(X - X_0)^2 + (Y - Y_0)^2 = R^2
\]

\[
(X - X_0)^2 + (Y - Y_0)^2 + (Z - Z_0)^2 = R^2
\]

\[
(R - \sqrt{(X - X_0)^2 + (Y - Y_0)^2 + (Z - Z_0)^2})^2 + (Z - Z_0)^2 = r^2
\]

It can be known that 3, 4, and 5 points can be collected for any 3, 4, and 5 points in three coordinates,
and the radius and position of the circle, sphere and ring can be calculated. In order to improve the measuring accuracy, the collected points should be as uniform as possible and walk on the measured surface. According to the analysis of the measuring principle, by measuring the diameter of the cylinder at both ends of the R0.8mm arc with a CMM, the position accuracy of the beginning and end points of the entire arc curve of the sealing surface can be judged. Then, the accuracy of the size contour and the accuracy of the tool tip arc can be verified by measuring the R0.8mm arc with CMM.

After the test is completed, the medium section is cut with the slow silk thread, and the size is tested repeatedly with the cutting test method. The test results show that the arc curves meet the design requirements.

The specific measuring method in the batch production process is as follows: the first product adopts CMM to measure the aperture accuracy at both ends of the R0.2mm arc, and confirms that the position of the starting and ending points and the machining curve of the whole NC program meet the accuracy requirements. For the subsequent products, the standard plug gauge and three-point internal diameter micrometer can be used to measure the aperture at both ends of the arc to improve the measuring efficiency, and then the surface quality of the valve orifice can be accurately judged by the microscopic measuring method with the aid of a 45-fold microscope[9].

2.3.2. The Application Effect of the Measuring Method

After the measuring method is applied, only the plug gauge and the CMM are needed in detecting, which can guarantee the measuring accuracy with the test equipment and reduce the influence factors of human, thus greatly improving the measuring accuracy. The comparison between the traditional processing and measuring methods of such products and the optimized methods is shown in table 3.

| Project type | Before | After |
|--------------|--------|-------|
| Method       | It can only be measured by cutting | CMM & plug gauge |
| Precision    | By the line cutting equipment and the level of the operator and other factors | It is guaranteed by the measuring equipment of CMM and plug gauge |
| Efficiency   | Unqualified need repeated processing cut, qualified products waste, low efficiency | Single measuring time less than 0.5h, and concrete value can be measured |

3. Conclusion

Although the machining performance of the soft magnetic alloy materials is poor, tiny arc structure of valve bodies were manufactured by the above machining and inspection methods. The standard tool combined with numerical control interpolation method is successfully realized to replace the profiling tool, and the measuring method of gauge combined with three-coordinates measuring machine is used to replace the sectioning inspection method. Experimental results showed the product qualified rate is increased from 60-70% to more than 96%, and the production efficiency is increased by three times. Therefore, this processing and inspection methods were recommended to manufacture other types of products with tiny arc.

Acknowledgments

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