Precision grinding process for gyro motor shaft of dynamic pressure air bearing

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Abstract—There are some problems of low accuracy, low efficiency and high cost in the precision machining for gyro motor shaft of dynamic pressure air bearing with high hardness and high brittleness, for the above questions, the research of high precision grinding technology is carried out. Firstly, the diamond grinding wheel is designed by studying the influence of different parameters on workpiece shape, surface quality and specific grinding energy, etc. Secondly, through the orthogonal test, the optimum process parameters affecting the surface roughness, roundness and cylindricity of motor shaft are determined. Finally, the grinding experiments of 20 motor shafts are completed by using the optimal parameters. The results showed that the qualified motor shaft with roundness 0.09μm, cylinder 0.32μm and roughness(Ra) 0.037μm is obtained when the workpiece speed is 308r/min, feed rate is 0.003m/min and grinding depth is 1μm.

1. INTRODUCTION
The dynamic pressure air bearing motor is the core component of liquid floating gyroscope. The motor shaft is made of steel bonded carbide (GT35), which is very hard and brittle. During machining, grinding wheel wear increases, resulting in burns on the processed surface and even minor cracks and tissue changes. At the same time, it is easy to produce processing stress that leads to collapse angle, surface and sub-surface crack and other problems, which cannot guarantee higher dimensional accuracy, shape and position accuracy, dimensional stability and surface roughness. At present, the machining precision is still achieved by manual grinding in the later stage. However, due to the influence of human factors, the grinding process leads to unstable manufacturing, poor dimensional consistency, worse shape and position accuracy of parts, and low production efficiency, which seriously hinders the development of liquid floating gyroscope\cite{1}.

Based on design and selection of super-hard grinding wheel for motor shaft of dynamic pressure air bearing, the research of processing technology is carried out. The motor shaft with roundness 0.09μm, cylindricity 0.32μm and roughness 0.037μm is obtained by using the online electrolytic dressing (ELID) technology. The processing technology proposed in this paper has proved the availability and superiority, and greatly improved the processing efficiency.
2. DESIGN AND SELECTION OF SUPER-HARD GRINDING WHEEL

2.1. Grinding wheel binder
GT35 material is a kind of engineering material between steel and carbide that made of powder metallurgy method preparation, it contains Mo 1%, Cr 5%, C 1%. After quenching, the hardness is HRA≥86, and the porosity is increased. Since the grinding wheel abrasives wear rapidly during machining, considering the requirement of good self-sharpness and elasticity, the diamond grinding wheel with cast iron binder is selected\[2\].

2.2. Grinding wheel granularity
Under the condition of fixed grinding parameters, the single-factor experiment method is adopted to study the influence law of grinding wheel granularity on surface roughness, and then the diamond grinding wheel suitable for particle size is selected at different grinding stages\[3\]. On the Studer30 external grinder, grinding wheels with particle sizes of 120#, 240# and 600# are selected to grind the motor shaft specimen respectively. The surface of the processed specimen is tested by the Taylor Hobson S4C profile meter. The results show that the roughness value of the processed surface increases with the increase of abrasive grain of the grinding wheel. Therefore, the grinding wheel granularity of 120# and 600# is selected for rough machining and finish machining respectively.

2.3. Shape and size of grinding wheel
In this study, the workpiece is grinded by using top hole location at both ends and fast point grinding technology\[4\]. Based on the mechanism of chip removal, the diameter of grinding wheel is determined to be 500mm. According to the geometric shape of the motor shaft in Figure.1, the diameter of (1) and (6) elements is 5mm, and (2) ~ (5) is 8mm. A uniform load of 1N/mm is applied to the center of the workpiece. Finite element analysis is conducted on the simply-supported beam to obtain the bending moment and deformation of the workpiece at various positions. When the center loading width of the grinding wheel is 3mm and 10mm, the center deformation is about 28nm and 90nm respectively.

![Figure 1. Analysis of grinding force on workpiece](image)

In conclusion, for the motor shaft precision machining, It is proposed to use thin plate diamond grinding wheel with cast iron base binder, Φ500mm in diameter, granularity for 120#, 600# respectively and width of 3mm.

3. PROCESSING TEST AND RESULT ANALYSIS
Three factors and levels of orthogonal test are carried out by taking the workpiece speed, cutting quantity and feed speed as factors, meanwhile, the roundness, cylindricity and roughness (Ra) as evaluation indexes. According to the process parameter, the motor shaft grinding test results are obtained as shown in Table 1.

| Test sequence | A: workpiece rotation speed. (r/min) | B: grinding depth. (µm) | C: feed speed. (m/min) | Roundness (µm) | Cylindricity (µm) | Roughness (µm) |
|---------------|------------------------------------|------------------------|------------------------|----------------|------------------|----------------|
| 1             | 120                                 | 1                      | 0.348                  | 2.28           | 2.34             | 0.054          |
| 2             | 120                                 | 3                      | 0.102                  | 1.1            | 2.26             | 0.057          |
| 3             | 120                                 | 5                      | 0.003                  | 0.25           | 2.12             | 0.040          |
| 4             | 210                                 | 1                      | 0.102                  | 0.86           | 0.87             | 0.057          |
| 5             | 210                                 | 3                      | 0.003                  | 0.41           | 0.54             | 0.038          |
3.1. Optimal level and combination of factors
Take the influence of each level of A (workpiece speed) factor on the test roundness index as an example. The influence of A1 is reflected in tests 1, 2 and 3, that of A2 is reflected in tests 4, 5 and 6, and that of A3 is reflected in tests 7, 8 and 9. The sum of the index corresponding to level 1 is calculated as follows:

\[ KA_1 = Y_1 + Y_2 + Y_3 = 2.28 + 1.1 + 0.25 = 3.63 \]  

(1)

In the same way, the level 2 corresponds to \( KA_2 = 3.30 \) and the level 3 is \( KA_3 = 1.87 \). According to \( KA_3 < KA_2 < KA_1 \), A3 can be judged as the optimal level of factor A. Similarly, the level of excellence of other factors can be calculated and determined. The optimal horizontal combination of three factors A3-B1-C3 is the optimal horizontal combination of roundness index in this test, that is, the optimal process parameters for GT35 dynamic pressure motor shaft grinding roundness are workpiece rotation speed 308r/min, grinding depth 1μm, and feed speed 0.003m/min. Similarly, A3-B1-C3 is also the optimal horizontal combination of cylindricity and roughness indexes in this experiment[5].

3.2. Primary and secondary order of factors.
The range value R reflects the fluctuation of the test index under a certain change of some factor[6]. According to the magnitude of R, the influence of each factor on the test index can be judged. For roundness, \( RC > RA > RB \), so the primary and secondary order of influence of each factor on roundness is C-A-B. In other words, the feed speed has the greatest influence, followed by the speed of workpiece, while the grinding depth has less influence. Similarly, the primary and secondary order of influence of each test factor on the two indexes of cylindricity and surface roughness is C-A-B.

| TABLE 2. OPTIMAL LEVEL AND COMBINATION OF FACTORS. |
|------------------|------------------|-----------------|
|                 | Roundness        |                 |
| K1               | 3.63             | 3.28            | 5.62            |
| K2               | 3.30             | 2.82            | 2.38            |
| K3               | 1.87             | 2.70            | 0.80            |
| R                | 1.76             | 0.58            | 4.82            |
| K1               | 6.72             | 3.67            | 7.11            |
| K2               | 4.66             | 4.32            | 4.30            |
| K3               | 3.15             | 6.54            | 3.12            |
| R                | 3.57             | 2.90            | 3.99            |
| K1               | 0.151            | 0.150           | 0.199           |
| K2               | 0.168            | 0.167           | 0.177           |
| K3               | 0.174            | 0.176           | 0.117           |
| R                | 0.023            | 0.026           | 0.082           |

3.3. The relationship between factors and indexes.
Test index of average level (Ki) and other factors have the following three aspects: one is when the workpiece speed increases, the number of abrasive grains passing through the grinding area increases per unit time greatly, each particle is not deformation cutting thickness decreases, while lead to the single particle grinding force decreases, and the grinding grain leaving scratches on the workpiece surface by a weakened and track density increases. Second, the grinding force increases with the increase of the grinding depth, resulting in serious deformation of the grinding wheel and the workpiece. At the same time, it will lead to intensified work hardening of the workpiece surface. Third, when the feed speed is increased, the force of the grinding wheel increases, and the scratches left by the grinding particle on the surface of the workpiece increase and the track density decreases[7]. To sum up, the
selection of higher workpiece speed, smaller grinding depth and slower feed speed is conducive to improving the workpiece processing accuracy.

![Figure 2. Surface metallographic diagram of 7 # motor shaft specimen](image)

![Figure 3. Section profile of 7 # motor shaft specimen](image)

The profile of the motor shaft grinding surface in Figure 2 can be observed in the same direction of scratches and randomly distributed on the surface of particle defects. One is the abrasive of the grinding wheel on the workpiece friction, plow and cutting to form the workpiece surface more regular texture[8]; The other is cemented carbide GT35 contains 35% TiC hard phase, the TiC particles of micron grade be squeezed to the steel bonded phase in the process of machining, machining on the surface of the rules in texture, and some particles under the action of abrasive grain from the surface to form pits, these pits to become lower the quality of workpiece surface, increase the surface roughness factor. It can be seen from Figure 3 that when the surface roughness of the plastic domain removal region is small, TiC particle shedding becomes the main factor to increase the surface roughness.

4. EXPERIMENTAL VERIFICATION OF OPTIMAL PARAMETERS
After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.
The grinding verification test of 20 motor shafts was carried out with the optimized grinding parameters. The optimal motor shaft roundness is 0.09μm, cylindricity is 0.32μm, roughness(Ra) is 0.037μm, and the production efficiency is greatly improved. See Figure.4 (a-c) for the inspection data of motor shaft processed by this process.

5. CONCLUSION

- ELID precision machining technology can be used to obtain qualified gyro motor shaft of dynamic pressure air bearing with high dimensional accuracy, shape and position accuracy, dimensional stability and low surface roughness.
When the speed of workpiece is 308r / min, feed speed is 0.003m/min, and grinding depth is 1μm, the optimal motor shaft roundness is 0.09μm, the cylindricity is 0.32μm, and the roughness(Ra) is 0.037μm. The main and secondary order of the influence of each experimental factor on cylindricity and surface roughness is that the feed speed has the greatest influence, the second is the workpiece speed, and the influence of the grinding depth is small.

The material removal mechanism of the motor shaft mainly includes two aspects: plastic region machining and hard phase particle shedding. In the grinding process, the plastic domain of the steel bond phase of the motor shaft is removed as the friction between the abrasive on the surface of the grinding wheel and workpiece, and the plough and cutting effect form a regular processing texture on the surface of the workpiece.

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