Process design and optimization Of Two-Stage Axial Micro Turbine Air motor

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Abstract. Based on the general machining center, a high-efficiency, mass-produced micro-turbine processing technology and a process scheme for improving metal removal rate are proposed to improve and optimize the metal removal rate of micro-machining. Taking the two-stage axial micro turbine air motor as the research object, the machining route of clamping the nozzle rotor is developed, and the metal removal rates of the turbine with the expandable surface when using the rounded end mill and the ball end mill are compared by the single factor analysis method. In the three processes of rough milling blade passage, finish milling blade and finish milling wheel hub, the metal removal rate of the rounded end mill is 2.96 times, 10 times and 2 times higher than the ball end mill, respectively. The Swarf finishing strategy of Powermill software is used to processing the side and bottom of the blade both roughly and accurately, and the suitable cutting parameters and side edge machining parameters are obtained. The surface roughness Ra of the side and bottom surfaces of the blade is tested to be 0.4-0.8μm using a surface roughness measuring instrument SJ-410. With the trigger type probe of the model Omp60, the dimensional tolerance of the blade is within 0.015 mm, and the coaxiality is from 0.002 to 0.003mm. The two-stage axial-type micro turbine air motor is assembled by the hot-packing method, and the torque and rotor speed are tested by a special platform. The results show that when the compressed air inlet pressure is 300KPa, the designed maximum speed of 100000rpm is satisfied, which meets the design requirement of the turbine motor and verifies that the numerical control machining process plan is feasible. Besides, the side edge machining of the blade using the cylindrical milling cutter is efficient to improve the metal removal rate. It also lays a foundation for the mass production of the two-stage axial-type micro turbine air motor.

1. Introduction

As a driving element of micro device, the axial-type micro turbine air motor has been widely applied in many products, such as micro spindle, micromechanics, portable energy, micro-engine, handpiece for dentists, and so on[1-6]. Micro turbine is the core part and its outer size is smaller than 20mm. The characteristic size of micro turbine belongs to mesoscale. Micro turbine is characteristic of complicated structure, high processing accuracy and high processing difficulties[7,8]. Many studies on processing of micro turbine have been reported in the world. Processing techniques of micro turbine are mainly divided into three types: The first type is MEMS micromachining technology represented by Massachusetts Institute of Technology (MIT)[9,10]. For example, MIT designed a radial-flow turbine in which the rotor diameter for micro turbine engine was 4.2mm and the pitch was only
0.225mm. Singapore Institute of Manufacturing Technology (SIMTech0 designed a turbine engine with 8.4mm rotor and 0.74mm thick blades[11-13]. This type of technologies depends on silicon microetching technology and is applicable to mass production, thus lowering the production cost. However, turbine blades can only be designed as 2D straight wall structures. The second type of technology refers to processing methods based on electrochemistry or electrocorrosion principle, such as plasma machining, laser processing and electrosparking processing [14,15]. The micro turbine engine developed by Catholic University of Leuven, Belgium, uses axial nozzle and rotor with a diameter of 10mm. It was developed through electrosparking [16-18]. This type of technologies can process small parts, but the processing efficiency is low. They are mainly used to process 2D straight walled blades. Although electrosparking can process turbine by manufacturing electrodes of 3D blade shape, the electrode has a micro-scale which is difficult for processing. Therefore, this type of technologies has low efficiency of mass production. The third type is precise micro-cutting technology represented by Tohoku University. Diameters of designed turbine and compressed blade were less than 20mm. It applied rounded milling cutter on five-axis precise processing center [19]. Liu kun et al [18] processed a centrifugal turbine with an outer diameter of 20mm on the universal five-axis processing center by using a rounded milling cutter with a diameter of 1mm. Micromachining is accomplished on a multi-axis CNC precision machine tool and turbine is processed by micro-cutter, thus enabling to get good surface roughness, accuracy and high processing efficiency. It is applicable to process micro or mesoscale 3D blade-shaped turbines [8,19]. However, this type of processing methods mainly focuses on feasibility of micro-cutting, but hasn’t discussed processing technique and processing efficiency deeply. Research conclusions are not promoted well.

In this study, a high-efficiency CNC processing technique based on universal processing center and the relevant optimization method for two-stage axial-type micro turbine air motor were proposed on the basis of micro-cutting technology. This processing technique is applicable to mass production of micro turbines. Firstly, processing scheme was formulated for nozzle and rotor of two-stage axial-type micro turbine air motor. Influencing factors of cutter and metal removal rates at processing of turbine were studied. Secondly, cutting path was planned by the computer assisted manufacturing software Powermill and the processing test was accomplished on the processing center. Quality of parts was tested by an in-built laser probe and surface roughness tester. Finally, the processed parts were assembled and performance of the assembly was tested on a special test platform to verify feasibility and validity of the proposed processing technique.

2. Structure of two-stage axial-type micro turbine air motor

2.1 Structure of air motor

Two-stage axial-type micro turbine air motor uses compressed air as a power to drive rotation of the rotor, thus driving working of drill, milling cutter and grinding head or microgenerator, and realizing transformation from gas compression energy to mechanical energy. Two-stage axial-type micro turbine air motor was mainly composed of shell, end cap, nozzle, turbine, principal axis, bearing and closing ring. The outer size was Ø30×58. The assemble profile is shown in Figure 1. The rotor system of the motor which is composed of level-1 and level-2 nozzle, rotor and principal axis is shown in Figure 2. During assembling, the rotor system is installed into the outer shell and the axial position of the rotor system is fixed by the closing ring. The end cap is rotated to adjust axial pretightening of rotor system and assure axial direction of principal axis runout within 0.01mm. When the turbine motor is working, compressed air flows in through the end cap. Airflow pressure decreases and the airflow velocity increases in the Level-1 nozzle. The compressed air flows to the rotor at a certain angle. In the rotor channel, airflow continues to be decompressed and accelerated to produce a counterforce on rotor. When airflow runs through the moving blade, an impact and a counterforce will be produced. Due to the resultant action of this impact and counterforce, the moving blade rotates around the axis, thus realizing high-speed rotation of the rotor system. The highest rotating speed and maximum torque of the prototype were designed 100000rpm and 6N.mm, respectively. It can be used as a driving element of micro devices,
such as micro-cutting, cell phone for dentists and micro dynamic devices.

Figure 1. Structure of the proposed air motor.

Figure 2. Rotor system of the proposed air motor.

2.2 Design parameters of the rotor system
The designed flow rate of the proposed air motor was 100L/min. Outer diameter of the nozzle and turbine was 20mm. Blade shape was designed with reference to standard blade type. To assure running stability and air consumption of the turbine motor, number of blades for nozzle and rotor were set 12, 11, 12 and 13 to assure relatively prime of number of blades between two adjacent turbines. With considerations to feasibility of processing equipment, the space between rotor of blades and outer shell is 50μm. The space between the level-2 nozzle and the principal axis is 40μm. Design parameters of the level-1 nozzle, level-2 nozzle and rotor are listed in Table 1. The sectional width of outlet (a) is the main parameter that determines diameter of the cutter in processing nozzles and turbine. It shall choose large-diameter cutter to protect enough stiffness while assuring allowance for finishing.

Table 1. Design parameters of nozzle and rotor.

| Name of parameters       | Level-1 nozzle 1S | Level-1 rotor 1R | Level-2 nozzle 2S | Level-2 rotor 2R |
|--------------------------|-------------------|------------------|-------------------|------------------|
| Outer diameter of turbine| 20                | 20               | 20                | 20               |
| Bottom diameter of turbine| 16                | 17.5             | 17.5              | 17               |
| Number of blades         | 12                | 11               | 12                | 13               |
| Width of blades (B)      | 7                 | 6                | 6                 | 4.83             |
| Pitch (t)                | 5.23              | 5.7              | 5.2               | 6                |
| Chord length (b)         | 7.5               | 6                | 7.1               | 6.05             |
| Sectional width at outlet (a) | 1.4              | 1.8              | 2.13              |

2.3 Material selection of different parts
Compared with blade-shaped air motor, turbine air motor has no wearing loss for no direct contact between blades and outer shell and thereby has longer service life [20]. To protect same thermal expansion characteristics of nozzle, rotor and outer shell, and prevent sticking or direct contact, the outer shell, turbine and nozzle were made of 7075 aluminium alloy. Considering to requirements on
working characteristics and corrosion resistance, principal axis of the motor was made of SUS304 stainless steel. The designed rotating speed of air motor is relatively high, it has to bear axial and radial forces at working. Hence, the front and back bearings chose silicon oxide ceramic principal axis bearings (SV786 C TA and HYSV789 CTA) made of GRW Company, Germany. The contact angle was set 15°. After assembling, the maximum allowable rotating speed of two bearings was 130,000rpm and the maximum affordable axial force was 300N.

3. Process optimization of micro turbine

3.1 Preparation of workblank and selection of processing equipments

Processing parts of turbine motor mainly include nozzle, turbine, principal axis and outer shell. To assure processing accuracy, all processing surfaces have to be clamped at once. To increase processing stiffness and increase clamping length of workblank, the principal axis workblank was made of ø10×66 stainless steel rods and shell workblank was made of ø35×85 alloy aluminum rods. Nozzle and turbine were made of ø25×50 alloy aluminum rods. Since outer shell and principal axis have high requirements on coaxiality, HTC2050im turning machine made by Shenyang Machine Tool Plant was chosen. It adopts full-closed ring control and FANUC Series oi-TD is used as CNC system. Positioning accuracy in the total excursion of 500mm is 5μm and the repeated positioning accuracy is 4μm. After once clamping, the external circular holes on the shell and principal axis as well as circumferential air holes can be processed. Principal axis and outer shell are generally processed by conventional processing method, which are not discussed in the following text.

Nozzle and turbine were processed by the DMU monoblock 100 universal CNC milling center made by DMG Company (Germany). This milling center applies the Heidenhain iTNC 530 CNC system and three straight feed shafts are X axis, Y axis and Z axis. Two rotating axes are C axis that can rotate around Z axis by 360° and the B axis that can swing around Y axis. The swinging angle of B axis ranges from +30° to -120°. The principal axis applies the HSK63A knife handle. The rotating speed can reach 24,000 and the processing accuracy is as high as 0.003mm. This principal axis can meet requirements on accuracy and form and location tolerance of nozzle and rotor.

3.2 Determination of processing route

Table 2. Milling operations for level-1 nozzle machining order.

| No. | Procedure            | Processing equipment Specification | Cutter Specification | Processing strategy                  | Programming mode |
|-----|----------------------|-----------------------------------|----------------------|--------------------------------------|------------------|
| 05  | Cylindrical milling  | Milling center DMU 100            | End mill ø8          | Cycl DEF 257 Circular Stud           | Manual           |
| 10  | Hole milling         | Milling center DMU 100            | End mill ø8.0        | Cycl def 252 circular pocket         | Manual           |
| 15  | Rough milling runner | Milling center DMU 100            | Rounded milling cutter | SWARF/ disc area cleaning of blade   | CAM              |
| 20  | Finish-milling blade | Milling center DMU 100            | Rounded milling cutter | SWARF/blade finishing                | CAM              |
| 25  | Fine wheel           | Milling center DMU 100            | Rounded milling cutter | SWARF/hub finishing                  | CAM              |
| 30  | Lathe cutting        | Turning center HTC2050im          | Cut-off tool G code  |                                                      | Manual           |

To assure high rotation accuracy and radial runout after assembly of turbine motor, cylindrical holes and blades of turbine are processed by clamping at a time. Since nozzle and rotor have similar structures, the same processing route was adopted (Table 2). This processing route includes 6 steps.
and the first five steps are accomplished on the milling center. Later, the plane end surface is cut on the turning center. For the convenience of program adjustment and measurement, cylindrical holes of nozzles and rotor are processed by manual programming. The milling cutter applies the integral carbide end mill made by Sandvik Coromant Company (Sweden) with a diameter of ø8. Rough machining and finishing of blades applies the automatic programming of Powermill10.0 of Delcam plc (UK). The corresponding turbine processing strategies include Swarf and rough machine and finishing of turbine. The Swarf processing strategy is a high-efficiency technique to process parts with side edge of end mill, which requires an extensible processing curved surface. Rough machining and finishing of turbine generally apply the ball milling cutter.

3.3 Selection and optimization of cutting tool

Characteristic size of nozzle and rotor is about 1mm, which belongs to mesoscale. It has to select cutter and cutting parameters reasonably. While assuring the processing accuracy, it has to increase metal removal rate and cutter stiffness, the formula of metal removal rate is

\[ Q = a_p \times a_e \times n \times f_z \times z \]  

where

- \( a_p \) —— cutting depth, mm
- \( a_e \) —— cutting width, mm
- \( Q \) —— metal removal rate, mm³/min
- \( n \) —— rotating speed of the cutter, r/min
- \( z \) —— number of edges of milling, pc
- \( f_z \) —— feeding amount per tooth, mm/edge
- \( D_{cap} \) —— cutting diameter at practical cutting depth

It can be seen from the Eq.(1) that three cutting factors, cutter structure and workpiece material all can influence metal removal rate during milling of turbine. Therefore, how to select the appropriate milling cutter and corresponding cutting parameters is very important. For existing micro turbine processing, rounded milling cutter is applied for blade milling. Rounded milling cutter has point contact theoretically and it has to decrease \( a_e \) and \( f_z \) to increase the high surface roughness. It can be seen from Figure 3 that during blade processing by ball milling cutter, the cutting diameter at practical cutting depth of ball milling cutter is \( D_{cap} < D_c \) when the cutting depth (\( a_p \)) is smaller than radius of the cutter (\( D_c \)), and \( D_{cap} = D_c \) at processing with a rounded milling cutter. Given the same processing residual area and service life of the cutter, ball milling cutter can only decrease the cutting width (\( a_e \)). Therefore, metal removal rate at processing an extensible curved surface with a rounded milling cutter is higher than that with a rounded milling cutter. For turbine with extensible curved pressure surface and suction surface, \( a_p \) and the processing efficiency can be increased significantly during finishing with the side edge of a rounded milling cutter.

| Step | Process               | Cutter /Size               | \( n \) r/min | \( f_z \) mm/z | \( a_p \) mm | \( a_e \) mm | \( Q \) mm³/min |
|------|-----------------------|----------------------------|---------------|----------------|--------------|-------------|----------------|
| 15   | Rough milling of channel | rounded milling cutter ø0.8R0.03 | 15000         | 0.002          | 0.02         | 0.74        | 0.888         |
|      |                       | rounded milling cutter ø0.8  | 15000         | 0.002          | 0.02         | 0.25        | 0.3           |
|      |                       | rounded milling cutter ø0.8R0.03 | 20000         | 0.0015        | 0.2          | 0.02        | 0.12          |
| 20   | Bade finishing        | rounded milling cutter ø0.8  | 20000         | 0.0015        | 0.02         | 0.02        | 0.012         |
|      |                       | rounded milling cutter ø0.8R0.03 | 20000         | 0.0015        | 0.03         | 0.2         | 0.36          |
| 25   | Hub finishing         | rounded milling cutter ø0.8  | 20000         | 0.0015        | 0.03         | 0.1         | 0.18          |
3.4 Implementation technique of turbine milling with a rounded milling cutter

To increase metal removal rate and shorten processing, nozzle 1 was processed by a rounded milling cutter. Other nozzles and rotors were processed by the same method of nozzle 1. During processing of nozzles and rotor, a three-jaw self-centering clamp was applied to prevent collision of five-axis processing center, the extending length of the clamped workpiece was no smaller than 30mm, while the height on the top surface of workblank and rotating table was higher than 200mm. The clamping mode of nozzle 1 is shown in Figure 4.

In Powermill software, turbine blades were processed by the Swarf strategy. To assure the cut-in and cut-out channels smooth, an arch transition curved surface was constructed at entrance of the turbine channel. Meanwhile, two ends of the curved surface was kept tangential with the pressure surface and suction surface of blades. Tangential extension was applied at outlet of the channel to assure smooth transition. During Swarf processing of slightly coarse milling channel, since the cutter diameter is close to sectional width at outlet (a), the Swarf processing strategy was applied twice by preserving residues. αp was set by multiple cutting technique. Cutting parameters are show in Table 3. Cutting route and cutter shaft are shown in Figure 4. At blade finishing and hub finishing, down milling was applied to assure processing accuracy and the hub finishing was accomplished by the tangential process between the bottom edge and hub processing. The outer size of the processed turbine is presented in Figure 3.

![Figure 3. Turbine processing on 5-axis machining center.](image)

![Figure 4. Machining tool path of Swarf.](image)

4. Analysis and discussion of turbine quality

4.1 Test of turbine surface roughness

Surface roughness of turbine may affect the flow field between blade lattices and a poor surface roughness may lead to complicated flowing, thickening boundary layer and reduced transformation efficiency of gases [22]. Therefore, surface roughness values of nozzle and rotor have to be tested. In this study, SJ-410 surface roughness gauge of Mitutoyo Company (Japan) was applied to test surface roughness of pressure surface, suction surface and bottom surface of blades. The driving range of the
driver of the gauge was 25mm and the straightness of the driver was 0.3μm. Resolution in 0.8mm was 0.01μm and the measuring strength was 4mN. The probe was made of diamond. A small-hole probe with outer diameter of Ø0.6mm was applied. The evaluation standard chose ISO1997[23] and the number of measuring samples was 5. The arithmetic mean surface roughness (Ra) was measured. Due to the microstructural size of turbine, turbine was sectioned at measuring and the separated turbine was fixed on a table of surface roughness gauge by using a clamping to make axial direction of blades parallel to the moving direction of driving detection part of surface roughness gauge. In this way, the axial surface roughness at bottom surface of the channel was tested. The radial direction of blade was kept parallel to the moving direction of driving detection part to test radial surface roughness of blades in the introduction segment of airflow streamline. Installation of the corresponding clamping is shown in Figure 5 and the test results are shown in Table 4. It can be seen from Table 4 that during blade milling with side edge under the same cutting parameters, roughness of the side surface and bottom surface of channel from nozzle 1 to rotor 2 is increased slightly compared with that of turbine. This is because sectional width at outlet increases along the flowing direction, which increases the diameter of rounded milling cutter, stiffness and surface roughness. The poorer bottom surface roughness of the same turbine compared with the side surface roughness is because the side surface is process at once by side edge of the milling cutter, while the bottom surface is formed by tangential processing between the bottom edge and arc of the bottom surface of the turbine.

The outer circle and internal hole of a turbine as well as coaxiality between the internal and external holes were tested by an in-built laser probe (Omp60 flip-over probe of Renishaw, UK) used in the five-axis CNC milling center. This probe is equipped with automatic reset in a 1μm range and high positioning accuracy and reset accuracy. The minimum internal diameter of measures was directly 6mm. The internal hole was used as the benchmark to measure coaxiality between the outer circle and internal hole. The coaxiality was within 0.002-0.003mm, indicating the high coaxiality of clamping process of internal and external holes at one time.

![Figure 5. Measurement of surface roughness.](image)

| Name  | Outer diameter (measured) | Inner diameter (measured) | Coaxiality (mm) | Bottom Ra | Side surface Ra |
|-------|--------------------------|---------------------------|-----------------|-----------|----------------|
| Nozzle 1 | Ø20 (Ø20.01) | Ø12 (Ø11.99) | 0.002 | 0.8 | 0.5 |
| Rotor 1  | Ø20 (Ø19.95) | Ø8 (Ø7.99) | 0.003 | 0.75 | 0.45 |
| Nozzle 2 | Ø20 (Ø20.00) | Ø8.5 (Ø8.55) | 0.002 | 0.73 | 0.43 |
| Rotor 2  | Ø20 (Ø19.93) | Ø9 (Ø9.05) | 0.003 | 0.7 | 0.4 |

There are interference fits between internal hole of nozzle and outer ring of bearing, between rotor and principal axis as well as between the principal axis and bearing. All parts were assembled by a hot
charging method. Firstly, rotor 2 was adhered onto the positioning axial order of the principal axis. Later, nozzle 2, rotor and nozzle 1 were assembled successively and the interval between different turbines was kept 1mm by a feeler gauge. The assembled rotor system is shown in Figure 6. After the rotor system was installed into an outer shell, the axial displacement of the rotor system was restricted by a closed ring and the bearing was pretightened by an end cap. With considerations to feasibility and economic efficiency of processing and transformation efficiency of air energy, the space between outer shell of the micro two-stage turbine air motor and the rotor and the between principal axis and nozzle were controlled within 0.04-0.05mm after assembly.

Figure 6. Turbine motor prototype and rotor system.

4.2 Working characteristics test of turbine
To test running effect of the assembled two-stage micro axial-type turbine air motor and thereby verify feasibility of CNC processing technique, the performance of air motor was tested on a special test platform. The test process is shown in Figure 7. This test platform can test inlet and outlet pressures of the air motor, inlet and outlet temperatures of stage-1 turbine, inlet and outlet temperatures of stage-2 turbine, mass flow of air and rotating speed of rotors. The collected data were transmitted to the upper computer through a data acquisition card and the working characteristics of two-stage axial-type micro turbine air motor were analyzed. The relation curve between inlet pressure and rotating speed of motor was drawn based on the collected data (Figure 8). When the inlet pressure was 300KPa, the maximum speed of the experiment was 100000RPM. The output total torque of the first and second stage turbine was 6.39N·mm for CFD and 5.72N·mm for the experiment, which met the design requirements. It showed that the turbines processed by the optimized process could meet the requirements of the motor, and the processing efficiency could be significantly improved.

Figure 7. Rotational speed test of turbine motor.
5. Conclusions

(1) A process optimization method of key parts of two-stage axial-type micro turbine air motor is studied and a CNC technique for mass processing nozzles and rotors on an universal five-axis CNC processing center is proposed. This technique formulates a processing route of nozzles and rotors. The positioning hole, external circle and channel are processed by clamping at one time. Coarse machining and finishing of side surface and bottom surface of blades are accomplished by the Swarf processing strategy of Powermill software. Appropriate parameter setting method and cutting parameters are gained through a cutting experiment. The surface roughness gauge and size accuracy of processed nozzles and rotors are tested. Roughness values of side surface and bottom surface of blades reach 0.4-0.8μm, and the tolerance in size is lower than 0.015mm. The coaxiality is between 0.002-0.003mm, meeting the design requirements of turbine.

(2) To increase metal removal rate and processing efficiency of nozzles and rotors as well as prolong service life of cutting tools, metal removal rates by using rounded milling cutter and ball milling cutter are compared through a quantitative analysis. During processing of nozzles and rotors with extensible curved surfaces, the rounded milling cutter increases metal removal rates at coarse milling of channel, blade finishing and hub finishing by 2.96 times, 10 times and 2 times compared with ball milling cutter. The processing efficiency is improved significantly.

(3) The two-stage axial-type micro turbine air motor is assembled by a hot charging method. Inlet pressure of the dynamic device and rotating speed of the rotor are tested by a special testing platform. When the inlet pressure of compressed air is 300KPa, it can reach the designed maximum rotating speed of 100,000rpm, indicating that the processed nozzles and rotors can meet design requirements. This lays foundations for mass production and further deep analysis of two-stage axial-type micro turbine air motor in future.

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