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Lei Zhang

Soochow University

Chen Ding

Soochow University

Cheng Fan (✉ chfan@suda.edu.cn)

Suzhou University

Lei Zhang

Jilin University

Qian Wang

Soochow University

Kejun Wang

Soochow University

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**Process planning of the automatic polishing of the
curved surface using a five-axis machining tool**

Lei Zhang¹, Chen Ding¹, Cheng Fan^{1,*}, Lei Zhang², Qian Wang¹, Kejun
Wang¹

*1 Jiangsu Provincial Key Laboratory of Advanced Robotics & Collaborative Innovation
Center of Suzhou Nano Science and Technology, Soochow University, Suzhou 215021,
China*

*2 School of Mechanical Science and Engineering, Jilin University, Changchun, 130025,
China*

*Contact: Cheng Fan.

E-mail: chfan@suda.edu.cn

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Abstract Curved surface parts are widely used in aerospace, automotive, electronic products and other fields due to their excellent aerodynamics, fluid dynamics and thermodynamics. Compared with the modeling technology of the curved surface, the development of the processing technology of the curved surface is slightly behind. In order to improve the processing quality and processing efficiency of the curved surface, this paper independently developed a five-axis CNC polishing machine tool, and studied the pre-processing and the post-processing when machining the curved surface. Taking a metal shell of the mobile phone as an example, three different paths are planned for the flat surface and the curved surface respectively, and a method for generating the tool path is proposed. The kinematics model of the five-axis CNC machine tool is established, which is used to obtain the calculation formula of the movement amount of each axis when polishing in the flat surface and the curved surface of the metal shell. Finally, the polishing effects of the different paths about the surface quality and the polishing efficiency of the metal shell are studied through the polishing experiments, and the polishing path with the best surface quality and the highest polishing efficiency is found.

Keywords: Curved surface, Path planning, Kinematics analysis, Polishing process

1 Introduction

The rapid development of the modern industry and its applications have put forward higher requirements on the appearance and performance of products. The products expressed by the curved surface are exquisite in appearance, controllable geometry, high degree of freedom, excellent aerodynamics and fluid dynamics, which have been widely used in products of all walks of life [1,2]. After decades of

development, the modeling technology of the curved surface has been relatively mature. However, because of its high requirements in precision and the difficulty of using mathematical expressions to accurately represent it, the curved surface machining has always been a major problem in the world today [3,4]. Polishing is essential for the traditional bathroom parts, shell parts in 3C industry and household kitchenware, and the key components in new industry such as blades, artificial bones, optical curved surfaces also require a final polishing process. As the last step in manufacturing process, the polishing process plays a vital role in the overall quality of the parts [5]. The traditional machining process of the curved surface adopts the ordinary machine tools or three-axis CNC machine tools, and then the final surface quality mainly rely on manual polishing. The surface quality after mannual polishing is poor and the polishing efficiency is low. In recent years, the performance of the CNC machine tools is improved greatly, especially the five-axis CNC machine tool, which integrates some advanced technologies such as computer control, high-performance servo drive and precision machining. Two rotation axes are added on the basis of the three-axis machine tools, which can avoid machining interference and improve the quality of the curved surface machining. After a workpiece is clamped, multi-face machining can be achieved, which improves the machining efficiency and the machining accuracy[6-8].

The path planning in the polishing process has a direct impact on the polishing efficiency, quality and accuracy, and is one of the most important research contents in the polishing process. The path planning is the process of planning the polishing path of the machine tool according to the shell model after forming. A reasonable polishing path can improve the machining efficiency and reduce the costs. The polishing path should meet the conditions of no interference, continuous smoothness

and high code quality [9,10]. The common methods of generating the tool path are isoparametric method [11,12], isometric section plane method [13,14], equal residual height method [15,16], etc. Sun[17] et al. proposed a method based on a polyhedron model with triangular mesh for generating the tool path, which can naturally form a machining path along polyhedron model, and can reduce the tool wear and machining time. Gershon[18] et al. proposed a simple and practical isoparametric tool path for free-form surface. Can[19] et al. proposed a new method based on the equal residual height method for generating the tool path and optimized the path, so that the overall length of the tool path was reduced and the machining efficiency was significantly improved. Senatore[20] et al. proposed a simplified method for calculating the interference judgment of isometric lines, which greatly improved the calculation efficiency. Ding[21] et al. proposed an adaptive equal-plane method and applied iso-illuminance method to divide the surface area. For different areas, they applied different plane spacing to intersect the curved surface, and adopted different tool path planning to improve the surface quality. The technology of generating the tool path is one of the important contents of the CNC machining technology. The choice of the method for generating the tool path should be determined by combining the nature of the workpiece to be processed, the type of CNC machine tool, the machining process, the tool used and the CNC system, so as to realize the high quality and high efficiency machining process according to the generated path. However, many researchers only studied the polishing path, and there is no systematic study on the pre-processing and the post-processing for the five-axis machining tool. On this basis, the innovation of this paper is that this paper combined the polishing path planning, generation of tool location, kinematic analysis and generation of NC code, and systematically studied the polishing

technology of the five-axis machine tool. The research process of this paper is shown in Figure 1.

This paper was organized as follows. In section 2, the specific structure of the machine tool and the polishing tool system is introduced. Taking a mobile phone with the metal shell as an example, the path of the cutter contact point was determined, and then the path of the cutter location point was obtained by calculation in the polishing process. In section 3, a mathematical model of the five-axis CNC machine tool is established, the kinematic analysis is carried out and the formula for solving the movement amount of each axis is derived. In section 4, a five-axis CNC machine tool is used to carry out the polishing experiment on the metal shell of the mobile phone. The experiment verified the rationality of the different polishing paths and measured the surface roughness of the sample after polishing. By analyzing the experimental results, the path with the best polishing effect and the highest polishing efficiency was found.

Figure 1 Process planning for polishing the curved surface

2 The five-axis CNC machine tool and the generation of the polishing path

2.1 The five-axis CNC machine tool

In this paper, a metal shell of the mobile phone is taken as an example to plan the polishing path, as is shown in Figure 2. The metal shell is mainly divided into three parts: the flat surface, the curved surface of edge and the high-gloss chamfered surface. Because the high-gloss chamfered surface is directly cut by the high-speed diamond cutter, it does not involve the polishing process. Thus, this paper only studies the generation of the polishing path of the flat surface and the curved surface. The overall size of the metal shell of the mobile phone is 150 mm×74.5 mm×7.6 mm, and the origin of the coordinate is established on the center of the flat surface.

Figure 2 The model of the metal shell of the mobile phone

According to the structural characteristics of the curved-surface products, a polishing CNC machine tool with five axes is developed as shown in Figure 3.

The five axes of the machine tool refer to the X axis, Y axis, Z axis, A axis and C axis, wherein the X axis, Y axis and Z axis are three linear axes, and the A axis and C axis are two rotation axes. The coordinate system of the machine tool is established according to the polishing system of the metal shell. Z axis is perpendicular to the clamped surface of the workpiece. Set right as the positive direction of X axis when viewing from the polishing system to the column. Y axis is determined by right-hand

Cartesian coordinate system after the positive direction of X axis and Z axis are determined. The positive directions of the A axis and C axis are determined according to the right-hand screw rule.

(a) The appearance of the machine tool (b) The internal structure of the machine tool

Figure 3 The polishing CNC machine tool with five axes

Figure 4 shows the model of the polishing tool system. The polishing tool system is mainly composed of a connecting plate of Z axis, a drive motor, a turbine reducer, a pneumatic locking device and a pneumatic rotation tool. Among them, the pneumatic rotation tool is mainly composed of the ventilation part, the sandpaper plate and the sponge sandpaper. Sponge sandpaper can be directly adhered to the sandpaper plate of the pneumatic rotation tool, which is driven by the pneumatic rotation tool at high speed. The pneumatic rotation tool can be fixed in a certain posture to polish the flat surface, or it can be driven by the drive motor to rotate around the A axis to polishing the curved surface of the edge.

Figure 4 The polishing tool system

2.2 Pre-processing for the polishing process

2.1.1 The path generation of the cutter location point of the flat surface

The size of the flat surface of the metal shell is 132mm × 60mm, and the diameter of the sponge sandpaper is 75mm. The data of the cutter contact point includes two parts: point data and normal vector data. The path of the cutter contact point of the flat surface is obtained by the model of the metal shell. When polishing the flat surface, the polishing ways include the lateral polishing, longitudinal polishing and diagonal polishing. In this section, three different polishing paths are planned according to the size of the flat surface and the diameter of the sponge sandpaper: "unilateral isoparametric path", "spiral isoparametric path" and "oblique cross path".

Let the thickness of the sponge sandpaper be h . The vertical distance between the working surface of the sandpaper plate and the A axis is R . The cutter location point can be obtained by offsetting the cutter contact point in the direction of the normal vector. The offset distance is the sum of the thickness of the sponge sandpaper and the vertical distance between the working surface of the sandpaper plate and the A axis, which is $R+h$. Let the coordinate of the cutter contact point be (x_i, y_i, z_i) . Let the normal vector of

the flat surface be (0, 0, 1). Then the calculation formula of the coordinate of the cutter location point (x_j, y_j, z_j) is

$$\begin{cases} x_j = x_i \\ y_j = y_i \\ z_j = z_i + R + h \end{cases} \quad (1)$$

As shown in Figure 5, by importing the coordinate value of the cutter location point in MATLAB, three different paths of the cutter location point can be obtained respectively.

(a) Unilateral isoparametric path (b) Spiral isoparametric path

(c) Oblique cross path

Figure 5 The paths of the cutter location point of the flat surface

2.1.2 The path generation of the cutter location points of the curved surface

When polishing the curved surface, the polishing ways include the annular polishing, lateral polishing and oblique polishing. According to the modeling characteristics of the curved surface, three different polishing paths of the cutter contact points are planned: “annular path”, “L-shaped path” and “V-shaped path”.

Figure 6 shows the schematic diagram for calculating the path of the cutter location point of the curved surface. Let the thickness of the sponge sandpaper be h . The vertical distance between the working surface of the sandpaper plate and the A axis is R . The cutter location point can be obtained by offsetting the cutter contact point in the direction of the normal vector. The offset distance is the sum of the thickness of the sponge sandpaper and the vertical distance between the working surface of the sandpaper plate and the A axis, which is $R+h$. Let the coordinate of the cutter contact point be $M(x_i, y_i, z_i)$. Let the unit normal vector be $P(l_i, m_i, n_i)$. Then the calculation formula of the coordinate of the cutter location point $N(x_j, y_j, z_j)$ is

$$\begin{cases} x_j = x_i + l_i \cdot (R + h) \\ y_j = y_i + m_i \cdot (R + h) \\ z_j = z_i + n_i \cdot (R + h) \end{cases} \quad (2)$$

Figure 6 The schematic diagram for calculating the path of the cutter location point of the curved surface

As shown in Figure 7, by importing the coordinate value of the cutter location point in MATLAB, three different paths of the cutter location point can be obtained respectively.

Figure 7 The paths of the cutter location point of the curved surface

3 Post-processing for the five-axis machining tool

The model of the workpiece can be used to generate the path of the cutter contact point and the normal vector of the cutter shaft, so as to obtain the path of the cutter location, which is pre-processing in the polishing process. However, the data file of the cutter location point generated by the pre-processing cannot be directly recognized and executed by the CNC system. Therefore, it is necessary to obtain the movement amount of each axis in the polishing process through kinematic analysis according to the specific structure of the machine tool, and then convert the movement data of each axis

into the NC code file that can be executed by the control system of the machine tool. The above process of converting the cutter location data file to NC code file is post-processing.

3.1 The kinematics model of the five-axis CNC machine tool

According to the structure of the five-axis CNC machine tool, the kinematic model of the machine tool is established as shown in Figure 8. The workpiece coordinate system is expressed as $O_W X_W Y_W Z_W$, and the origin of the coordinate is established at the center of the flat surface of the metal shell. The coordinate system of C axis is expressed as $O_C X_C Y_C Z_C$, and the origin of the coordinate is established at the rotation center of the C-axis turntable. The Z_C axis and the Z_W axis are on the same straight line. The coordinate system of Y axis is expressed as $O_2 X_2 Y_2 Z_2$, and the origin of the coordinate is established at the center of the saddle surface of the Y-axis electric actuator. The coordinate system of the machine tool is expressed as OXYZ, and the origin of the coordinate is established at the zero point of the machine tool. The coordinate system of X axis is expressed as $O_1 X_1 Y_1 Z_1$, and the origin of the coordinate is established at the center of the saddle surface of the X-axis electric actuator. The coordinate system of Z axis is expressed as $O_3 X_3 Y_3 Z_3$, and the origin of the coordinate is established at the center of the saddle surface of the Z-axis electric actuator. The coordinate system of A axis is expressed as $O_A X_A Y_A Z_A$, and the origin of the coordinate is established at the rotation center of the A axis. The coordinate system of the tool is expressed as $O_T X_T Y_T Z_T$, and the origin of the coordinate is established at the rotation center of the pneumatic rotation tool. The Y_T axis and the Y_A axis are on the same straight line. The coordinate of the origin of the tool coordinate system in the A-axis coordinate system is (0, b, 0).

Figure 8 The kinematics model of the five-axis CNC machine tool

By analyzing the kinematics model, the polishing motion of the machine tool can be regarded as the synthetic motion of each coordinate system. The kinematic chain is shown in Figure 9.

Figure 9 The kinematic chain of the five-axis CNC machine tool

3.2 Inverse kinematics of the five-axis machine tool

The solution of the inverse kinematics is a process of solving the movement amount of each axis of the machine tool according to the data of the cutter location point generated by pre-processing, also known as kinematics analysis. The movement amount of each axis of the five-axis CNC machine tool includes the movement amount along X axis, the movement amount along Y axis, the movement amount along Z axis, the rotation amount of A axis and the rotation amount of C axis, which are respectively expressed

by dx , dy , dz , θ_x and θ_z . When solving the movement amount of each axis, according to the principle that the workpiece is relative rest and the tool is relative motion, the origin of the cutter coordinate system is transformed to the workpiece coordinate system through coordinate transformation and coincides with the cutter location point. It is also necessary to ensure that the normal vector of the cutter shaft is parallel to the space normal vector of each cutter location point. Through the movement of three linear axes, the origin of the cutter coordinate system is ensured to coincide with the cutter location point. Through the rotation of two rotation axes, the normal vector of the cutter shaft is ensured to be parallel to the normal vector of each cutter location point.

3.2.1 Solving the rotation angle around A axis and C axis

First of all, the rotation angles around A axis and C axis are calculated according to the normal vector of the cutter contact point. Because the normal vector of the cutter contact points can be used to describe the attitude of the cutter shaft, this normal vector can be coincident with the origin of the workpiece coordinate system during the analysis. As is shown in Figure 10, the workpiece coordinate system is expressed as $O_W X_W Y_W Z_W$. The unit normal vector of the cutter shaft is $\mathbf{O}_W \mathbf{T} = (l_i, n_i, m_i)$. In order to make the normal vector of the cutter shaft parallel to the positive direction of the Z_W axis, first rotate the normal vector of the cutter shaft anticlockwise around the Z_W axis by angle θ_z to the plane $Y_W Z_W$, and then rotate it anticlockwise around the X_W axis by angle θ_x to Z_W axis.

Figure 10 The rotation diagram of the normal vector of the cutter shaft

According to the geometrical relationship in Figure 10, the following formulas can be derived:

$$\begin{cases} \theta_x = \arctan(n_i / \sqrt{l_i^2 + m_i^2}) - \pi/2 \\ \theta_z = \arctan(m_i / l_i) - \pi/2 \end{cases} \quad (3)$$

3.2.2 Solving the movement amount along X axis, Y axis and Z axis

According to the inverse kinematics, the movement amounts of the machine tool along X axis, Y axis and Z axis are solved as follows.

The transformation matrix of the origin of the cutter coordinate system in the A-axis coordinate system is

$$Trans(0, b, 0) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

The transformation matrix rotating around the A axis is

$$Rot(x, \theta_x) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_x & -\sin \theta_x & 0 \\ 0 & \sin \theta_x & \cos \theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

The transformation matrix of the origin of the A-axis coordinate system in the cutter coordinate system is

$$Trans(0, -b, 0) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

The transformation matrix of the cutter coordinate system moving along the X axis, Y axis, and Z axis in the workpiece coordinate system is

$$Trans(d_x, d_y, d_z) = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

The transformation matrix rotating around the C axis is

$$Rot(z, \theta_z) = \begin{bmatrix} \cos \theta_z & -\sin \theta_z & 0 & 0 \\ \sin \theta_z & \cos \theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

M_{WT} is used to represent the transformation matrix that coincides the origin of the cutter coordinate system with the cutter location point in the workpiece coordinate system.

$$M_{WT} = Rot(z, \theta_z) \cdot Trans(d_x, d_y, d_z) \cdot Trans(0, -b, 0) \cdot Rot(x, \theta_x) \cdot Trans(0, b, 0) \quad (9)$$

295 The coordinate of the cutter location point in the workpiece coordinate system is

$$296 \quad p_w = \begin{bmatrix} x_j & y_j & z_j & 1 \end{bmatrix}^T \quad (j=1,2,\dots,n) \quad (10)$$

297 The coordinate of the origin of the cutter coordinate system in the cutter coordinate
298 system is

$$299 \quad p_T = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T \quad (11)$$

300 The origin of the cutter coordinate system is transformed to the workpiece coordinate
301 system through coordinate transformation and coincides with the cutter location point,
302 that is

$$303 \quad p_w = M_{wT} \cdot p_T \quad (12)$$

304 By solving the Equation (12), the movement amount along X axis, Y axis and Z axis
305 can be obtained.

$$306 \quad \begin{cases} d_x = x_j \cdot \cos \theta_z + y_j \cdot \sin \theta_z \\ d_y = -x_j \cdot \sin \theta_z + y_j \cdot \cos \theta_z - b \cdot \cos \theta_x + b \\ d_z = z_j - b \cdot \sin \theta_x \end{cases} \quad (13)$$

307 Equation (3) and Equation (13) constitute the movement amount of each axis of the
308 machine tool, that is

$$309 \quad \begin{cases} d_x = x_j \cdot \cos \theta_z + y_j \cdot \sin \theta_z \\ d_y = -x_j \cdot \sin \theta_z + y_j \cdot \cos \theta_z - b \cdot \cos \theta_x + b \\ d_z = z_j - b \cdot \sin \theta_x \\ \theta_x = \arctan(n_i / \sqrt{l_i^2 + m_i^2}) - \pi/2 \\ \theta_z = \arctan(m_i / l_i) - \pi/2 \end{cases} \quad (14)$$

When polishing the flat surface of the metal shell, all the points in the flat surface are in the XOY plane, so the normal vectors of all the polished points in the flat surface are (0, 0, 1). By substituting it into Equation (14), the formula for calculating the movement amount of each axis when polishing in the flat surface can be obtained.

$$\begin{cases} d_x = -y_j \\ d_y = x_j \\ d_z = z_j \\ \theta_x = 0 \\ \theta_z = -\pi/2 \end{cases} \quad (15)$$

Equation (15) is solved by the superposition of the center point of the pneumatic rotation tool and the cutter contact point of the metal shell. When polishing the curved surface of the metal shell, in order to prevent the collision between the pneumatic rotation tool and other mechanisms, the position of the pneumatic rotation tool needs to be adjusted in the YOZ plane, as is shown in Figure 11.

Figure 11 Adjusting the position of the tool

Move the axis of the pneumatic rotation tool from point A to point B along the tangent direction of the polished point. The distance between the point A and point B is

325 l . The initial position of the axis of the pneumatic rotation tool is vertical. In the position
 326 shown in the Figure 11, the axis of the pneumatic rotation tool turns clockwise by an
 327 angle θ_x . In the process of moving the axis of the pneumatic rotation tool from point A
 328 to point B, the movement amount of Y axis increases by $l \cdot \cos(-\theta_x)$ and the movement
 329 amount of Z axis reduces by $l \cdot \sin(-\theta_x)$. By substituting the increasement of Y axis and
 330 the decreasement of Z axis into the equation (14), we can get the calculation formula of
 331 the movement amount of each axis when polishing the curved surface of the metal shell,
 332 which gives

$$333 \quad \begin{cases} d_x = x_j \cdot \cos \theta_z + y_j \cdot \sin \theta_z \\ d_y = -x_j \cdot \sin \theta_z + y_j \cdot \cos \theta_z - b \cdot \cos \theta_x + b + l \cdot \cos(-\theta_x) \\ d_z = z_j - b \cdot \sin \theta_x - l \cdot \sin(-\theta_x) \\ \theta_x = \arctan(n_i / \sqrt{l_i^2 + m_i^2}) - \pi/2 \\ \theta_z = \arctan(m_i / l_i) - \pi/2 \end{cases} \quad (16)$$

334 In conclusion, the calculation formulations of the inverse kinematics of the machine
 335 tool are shown in Table 1.

336 **Table 1** The calculation formulations of inverse kinematics of the machine tool

Polishing position	Calculation formulations
Flat surface	$\begin{cases} d_x = -y_j \\ d_y = x_j \\ d_z = z_j \\ \theta_x = 0 \\ \theta_z = -\pi/2 \end{cases}$

$$\text{Curved surface} \quad \left\{ \begin{array}{l} d_x = x_j \cdot \cos \theta_z + y_j \cdot \sin \theta_z \\ d_y = -x_j \cdot \sin \theta_z + y_j \cdot \cos \theta_z - b \cdot \cos \theta_x + b + l \cdot \cos(-\theta_x) \\ d_z = z_j - b \cdot \sin \theta_x - l \cdot \sin(-\theta_x) \\ \theta_x = \arctan(n_i / \sqrt{l_i^2 + m_i^2}) - \pi/2 \\ \theta_z = \arctan(m_i / l_i) - \pi/2 \end{array} \right.$$

4 Experiments

4.1 Planning of the experiments

According to the contents of the path planning in section 2, three different polishing paths are generated for the flat surface and the curved surface of the sample respectively. Then, by using the post-processing technology to convert the data file of the cutter location point into NC code file, the polishing experiment can be carried out by the five-axis CNC machine tool. The experiments are carried out in three groups, and the path forms of three groups are shown in Table 2.

Table 2 The path forms of the polishing experiment

Number	Path forms of the curved surface	Path forms of the flat surface
1	Annular path	Spiral isoparametric path
2	L-shaped path	Unilateral isoparametric path
3	V-shaped path	Oblique cross path

In the process of the polishing experiment, the curved surface is first polished, and then the flat surface is polished. By using the drawing function of MATLAB, three paths of the cutter contact point are shown in Figure 12 (a), Figure 12 (b) and Figure 12 (c) respectively.

(a) The path of the cutter contact point in Experiment 1 (b) The path of the cutter contact point in Experiment 2

(c) The path of the cutter contact point in Experiment 3

Figure 12 The paths of the cutter contact points in three experiments

The abrasive of the sponge sandpaper is alumina, and the basal body is foamed PU sponge. The original thickness of the sponge sandpaper is 5mm. The sponge sandpaper with particle size of P800 is selected for coarse grinding and P1800 is selected for fine grinding. The specific parameters of the experiment are shown in Table 3.

Table 3 The parameters of the experiment

Parameters	Value
Revolving speed of the polishing tool system	1000r/min
Feed speed	2500 mm/min
Grinding fluid ratio	1:30
Downpress amount of sponge sandpaper	1mm

Particle size of the sponge sandpaper for coarse grinding	P800
Particle size of the sponge sandpaper for fine grinding	P1800

4.2 Result and discussion

During the polishing experiment, the polishing state of the four typical positions of the metal shell are shown in Figure 13. The four typical positions of the metal shell are arc sphere of the curved surface, the short arc cylinder of the curved surface, the long arc cylinder of the curved surface and the flat surface.

(a) Polishing arc sphere

(b) Polishing the short arc cylinder

(c) Polishing the long arc cylinder

(d) Polishing the flat surface

Figure 13 The polishing state of four typical positions

The polishing time of the flat surface and the curved surface were counted respectively in Experiment 1, Experiment 2 and Experiment 3 and the surface roughness of the flat surface and the curved surface were measured respectively in Experiment 1,

Experiment 2 and Experiment 3. The sampling length is 0.8mm, and the evaluation length is 5 times of the sampling length. The digital filter is Gaussian filter. The experimental data is summarized in Table 4.

Table 4 The surface roughness and the polishing time of the polished sample

Experiment number	Surface roughness (Ra/ μm)		Polishing time (T/s)	
	Curved surface	Flat surface	Curved surface	Flat surface
1	0.2729	0.2392	42	9
2	0.2196	0.2106	112	7
3	0.1798	0.1608	104	12

As is shown in Figure 14(a) and Figure 14(b), the surface roughness of the curved surface of the unpolished sample is $0.7286\mu\text{m}$ and the surface roughness of the flat surface of the unpolished sample is $0.6968\mu\text{m}$. The surface roughness of the unpolished sample is large and the surface is uneven.

As is shown in Figure 15(a), Figure 16(a) and Figure 17(a), the surface roughness of the curved surface in three experiments are $0.2972\mu\text{m}$, $0.2196\mu\text{m}$ and $0.1978\mu\text{m}$ respectively. As is shown in Figure 15(b), Figure 16(b) and Figure 17(b), the surface roughness of the flat surface in three experiments are $0.2392\mu\text{m}$, $0.2106\mu\text{m}$ and $0.1608\mu\text{m}$ respectively. The profile of the surface roughness is more uniform compared with the unpolished sample and the surface quality is improved. Among three experiments, the surface roughness in Experiment 3 is the smallest, and the polishing effect is the best. The surface roughness of the flat surface and the curved surface both meet the requirement .

By comparing the surface roughness of three experiments, it can be concluded that the surface roughness of the curved surface is larger than that of the flat surface. This is because when polishing the sample, the curved surface is first polished and then the flat

surface is polished. The abrasive distributed on the sponge is sharper at the beginning of the polishing process. With the development of the polishing process, the sharp abrasive is gradually smoothed and the distribution of the abrasive is more uniform, so the above phenomenon appears.

Comparing the polishing time of three experiments, the polishing time of Experiment 1 is the shortest and the polishing efficiency is the highest when polishing the curved surface of the sample. When polishing the flat surface of the sample, the polishing time of Experiment 2 is the shortest and the polishing efficiency is the highest. However, the surface roughness of two parts of the sample in Experiment 1 and Experiment 2 does not meet the requirement after polishing.

From the above, considering the effects of surface roughness and the polishing efficiency, the polishing path of Experiment 3 is selected in the actual polishing process.

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 14 The surface roughness of the unpolished sample

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 15 The surface roughness of Experiment 1

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 16 The surface roughness of Experiment 2

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 17 The surface roughness of Experiment 3

5 Conclusions

In this paper, a polishing CNC machine tool with five-axis was developed according to the characteristics of the curved surface. Taking a metal shell of the mobile phone as an example, three paths named "unilateral isoparametric path", "spiral isoparametric path" and "oblique cross path" were planned for polishing the flat surface, and three paths named "annular path", "L-shaped path" and "V-shaped path" were planned for polishing the curved surface. Established the kinematics model of the five-axis CNC machine tool, and analyzed the kinematics model to obtain the calculation formula of the movement amount of each axis when polishing in the flat surface and the curved surface of the metal shell.

The polishing experiments were carried out by the five-axis CNC machine tool to polish the surface of the metal shell. The surface roughness of the curved surface in three experiments are $0.2972\mu\text{m}$, $0.2196\mu\text{m}$ and $0.1978\mu\text{m}$ respectively, and the surface roughness of the flat surface in three experiments are $0.2392\mu\text{m}$, $0.2106\mu\text{m}$ and $0.1608\mu\text{m}$ respectively. Among three experiments, the surface roughness in Experiment 3 is the smallest, and the polishing effect is the best. The surface roughness of the flat

surface and the curved surface both meet the requirement. Comparing the polishing time of three experiments, the polishing time of Experiment 1 is the shortest and the polishing efficiency is the highest when polishing the curved surface of the sample. When polishing the flat surface of the sample, the polishing time of Experiment 2 is the shortest and the polishing efficiency is the highest. However, the surface roughness of two parts of the sample in Experiment 1 and Experiment 2 does not meet the requirement after polishing. From the above, considering the effects of surface roughness and the polishing efficiency, the polishing path of Experiment 3 is selected in the actual polishing process.

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Competing interests

The authors declare that they have no competing interests.

Authors' contributions

LZ and CF were in charge of the whole trial and developed the polishing machine. CD and LZ wrote the manuscript. QW and KW conceived the study and participated in its design and coordination. All authors read and approved the final manuscript.

Authors' information

Lei Zhang, born in 1970, is a professor of School of Mechanical and Electrical Engineering, Soochow University, Soochow, Jiangsu Province, China. He received his Ph.D. degree in Mechanical Engineering from Jilin University of Technology, China, in 1999. His research interests include Grinding and Polishing of Freeform Surfaces.

Cheng fan, born in 1986, is an associate professor in School of mechanical and electrical engineering of Soochow University. He received his Ph.D in School of Mechanical Science and Engineering of Jilin University. His research interests include precision polishing and bionic sensor.

Chen Ding, born in 1994, is a graduate student in School of mechanical and electrical engineering of Soochow University. His research interests include belt polishing for blisk.

Lei Zhang, born in 1992, is a graduate student in School of Mechanical Science and Engineering of Jilin University. His research interests include free-form surface polishing.

Qian wang, born in 1991, is a lecturer of School of mechanical and electrical engineering, Soochow University, Soochow, Jiangsu Province, China. She received her

Ph.D from Key laboratory of bionic engineering, ministry of education of Jilin University. Her research interests include mechanical bionics and sensor.

Kejun wang, born in 1989, is a lecturer of School of mechanical and electrical engineering, Soochow University, Soochow, Jiangsu Province, China. He received his Ph.D in Bionic Science and Engineering of Jilin University. His research interests include sensor and mechanical polishing.

Author Details

¹ Jiangsu Provincial Key Laboratory of Advanced Robotics & Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou 215021, China. ² School of Mechanical Science and Engineering, Jilin University, Changchun, 130025, China

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Figures

Figure 1

Process planning for polishing the curved surface

Figure 2

The model of the metal shell of the mobile phone

(a) The appearance of the machine tool (b) The internal structure of the machine tool

Figure 3

The polishing CNC machine tool with five axes

Figure 4

The polishing tool system

Figure 5

The paths of the cutter location point of the flat surface

Figure 6

The schematic diagram for calculating the path of the cutter location point of the curved surface

Figure 7

The paths of the cutter location point of the curved surface

Figure 8

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graph LR
    A[Pneumatic rotation tool] --> B[The coordinate system of A axis]
    B --> C[The coordinate system of Z axis]
    C --> D[The coordinate system of X axis]
    D --> E[The coordinate system of the machine tool]
    E --> F[The coordinate system of Y axis]
    F --> G[The coordinate system of C axis]
    G --> H[The workpiece coordinate system]
  
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The kinematic chain of the five-axis CNC machine tool

Adjusting the position of the tool

(a) The path of the cutter contact point in Experiment 1 (b) The path of the cutter contact point in Experiment 2

(c) The path of the cutter contact point in Experiment 3

Figure 12

The paths of the cutter contact points in three experiments

(a) Polishing arc sphere

(b) Polishing the short arc cylinder

(c) Polishing the long arc cylinder

(d) Polishing the flat surface

Figure 13

The polishing state of four typical positions

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 14

The surface roughness of the unpolished sample

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 15

The surface roughness of Experiment 1

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 16

The surface roughness of Experiment 2

(a) Roughness of the curved surface

(b) Roughness of the flat surface

Figure 17

The surface roughness of Experiment 3