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Research Article

Simulation of Constant-Volume Removal Rate Machining of Middle-Convex and Varying Ellipse Piston

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One kind of constant-volume removal rate machining method of the middle-convex and varying ellipse piston is proposed in this paper. By analyzing the structure and movement relationship of the middle-convex and varying ellipse piston machine, the NC machining model is built. And, the constant-volume removal rate machining model is also built by superposing the variable rotation satisfying the dynamic performance constraints on the uniform rotation of the spindle of the CNC piston lathe. Then, the instantaneous position parameters of each axis of the CNC piston lathe are obtained and turned into NC code. The functional feasibility of the method finally is verified by simulation machining.

1. Introduction

In the reciprocating process of crankshaft output torque, the piston transmits the gas pressure in the cylinder to this process through the piston pin and connecting rod, but the clearance between the piston and the cylinder sleeve should be as small and uniform as possible to prevent the piston from being “roughened” or “bitten” in the cylinder. However, in the coupled working environment of high temperature, high pressure, and alternating mechanical and thermal loads, the force acting on the top of the piston leads to the deformation of the piston skirt along the axis of the pin seat, the deformation of the side of the piston skirt, and the uneven thermal expansion. These causes lead to serious and irregular deformation of the piston, which makes the cross section of the piston skirt that is originally a round cross section cannot keep round in the working environment, and then become oval, resulting in that the “cylindrical” piston processed at room temperature presents the “elliptical cylinder” shape. This deformation directly affects the uniformity of fit clearance between piston and cylinder liner. The piston with middle-convex and varying ellipse piston skirt is designed, which can keep the ideal geometry under working conditions [1], ensure the good fit between the piston and the cylinder wall, reduce the cylinder clearance and the impact of the piston on the cylinder wall, and reduce the specific pressure and noise of the piston skirt. Moreover, a wedge-shaped oil gap is formed between the middle-convex skirt of the piston and the cylinder wall, which ensures the good lubrication of the piston and reduces the wear of parts.

For a long time, many scholars have deeply studied the machining method of middle-convex and varying ellipse piston [2–12].These achievements have effectively promoted the progress of machining technology of middle-convex and varying ellipse piston, but the noncircular section machining technology of piston skirt studied by these achievements is basically based on numerical control turning method. NC turning is an important method for machining the piston with middle-convex and varying ellipse piston, which can effectively improve the machining accuracy and efficiency of the piston with middle-convex and varying ellipse piston. However, in the process of cutting a circular cross-sectional workpiece into an elliptical cross-sectional workpiece on a CNC piston lathe, the workpiece will rotate at a constant speed, and the cutting tool will move with high frequency and reciprocation. Moreover, the cutting depth of the cutting tool will change continuously with the rotation position of the workpiece, and the cutting area of the cutting tool in the same cross section will change with the processing position. The material removal rate and cutting force of the workpiece change periodically, which will form dynamic excitation force and affect the machining accuracy of piston skirt to a certain extent.

Based on the basic principle that the cutting force is approximately proportional to the cutting area, this paper studies the numerical control machining technology and simulation of the equal volume cutting rate of the middle-convex and varying ellipse piston. On the premise that the rotation position of the shaft section of the piston skirt and the cutting depth of the tool tip conform to the ellipse trajectory, the variable-speed rotation meeting the dynamic performance constraint is superimposed on the uniform speed rotation of the main shaft of the piston machine tool. The rotation speed of the main shaft of the machine tool is continuously regulated, and the material removal rate and cutting force of the middle-convex and varying ellipse piston skirt are basically constant.

2. Processing Principle of Middle-Convex and Varying Ellipse Piston Skirt

The profile characteristics of the middle-convex and varying ellipse piston skirt are as follows: the generatrix of the piston skirt is a middle-convex curve which represents the variation of the diameter of the long axis of the elliptic section along the direction of the piston axis. The shape of cross section of piston skirt is similar to an ellipse, and the ovality of different sections is different. In any section, the diameter of long axis of ellipse section is the largest diameter, the long axis is along the axis of pin seat, the diameter of short axis of this section is the smallest diameter, and the short axis is perpendicular to the axis of pin seat. The ellipticity of the elliptic section is the difference between the diameter of major axis and that of minor axis.

2.1. Elliptical Profile of Skirt Cross Section of Middle-Convex and Varying Ellipse Piston. The geometric characteristics of the skirt cross section of the piston with middle-convex and varying ellipse can be described as follows [2]:

$$R(h,\theta) = R_1(h) - \frac{G(h)}{4}C. \tag{1}$$

In the formula, $R(h,\theta)$is polar radius value;$G(h)$is ellipticity; and $R_1(h)$is elliptical long half-axis.

$$R_1(h) = R_1(0) - k_1(h-h_0)^m. \tag{2}$$

In the formula, $R_1(0)$is long half-axis of section with maximum ellipticity.

$$G(h) = G(0) - k_2 h. \tag{3}$$

In the formula,$G(0)$is the maximum ellipticity; θ isthe relative rotation angle of polar radius to long axis; h is the skirt height; $h_0$is the skirt height of section with maximum ellipticity; $\beta$is the dimensionless coefficient ($\beta = 0$ is an ellipse; $\beta = 1$ is a quadratic ellipse); $m$is the profile shape characteristic coefficient of longitudinal profile; $k_1$is the dimensionless coefficient; and $k_2$is the ellipticity change rate.

$$C = 1 - k_3\left\{\cos 2\theta - \frac{\beta}{25}[1-\cos 4\theta]\right\}. \tag{4}$$

In the formula, $k_3$is the dimensionless coefficient (when $k_3 = 0$, the cross section is circular; when $k_3 = 1$, the cross section is elliptical).

Formula (1) is the variation of polar radius, and formula (2) is the radial variation of the middle-convex profile along the piston axis. If the piston is an elliptical piston, the formula of any elliptical cross section of the piston skirt can be obtained by substituting formula (4) into (1).

$$R(h,\theta) = R_1(h) - \frac{G(h)}{4}(1-\cos 2\theta), \tag{5}$$

among which, $\theta = \omega t = 2\pi nt/60 = 2\pi ft$, ω is angular velocity, and

$$R(h,\theta) = R_1(h) - \frac{G(h)}{4}[(1-\cos 2\theta) + \beta(1-\cos 4\theta)]. \tag{6}$$

2.2. Middle-Convex Profile of Middle-Convex and Varying Ellipse Piston. The middle-convex profile of the middle-convex and varying ellipse piston skirt is usually given discrete points in design. Figure 1 is the design parameters of the middle-convex profile of the Perkins 240 piston skirt.

Usually, the discrete points of the convex profile are fitted to smooth curves by cubic spline interpolation, and then the equation of the middle-convex profile is obtained. In the process of fitting the discrete points of middle-convex profile in piston skirt shown in Figure 2, N discrete points are put into the XOZ coordinate system in which the X-axis is parallel to the piston cross section and the Z-axis is the piston axis (X represents the long half-axis of elliptical cross section and Z represents the piston skirt height). If the first derivatives of the curve composed of discrete points are x_0' and x_n' at the beginning and end points, respectively, the function value $x(z)$ of any point $z_{i-1} < z < z_i$on the Z-axis can be expressed as follows [13]:

$$\begin{aligned} x(z) = {} & M_{i-1}\frac{(z_i - z)^3}{6L_i} - \frac{(z - z_{i-1})^3}{6L_i} \\ & + \left(\frac{x_i}{L_i} - \frac{M_i L_i}{6}\right)\cdot(z - z_{i-1}) \\ & + \left(\frac{x_{i-1}}{L_i} - \frac{L_i M_{i-1}}{6}\right)\cdot(z_i - z). \end{aligned} \tag{7}$$

In the formula, $M_i$satisfies the equation

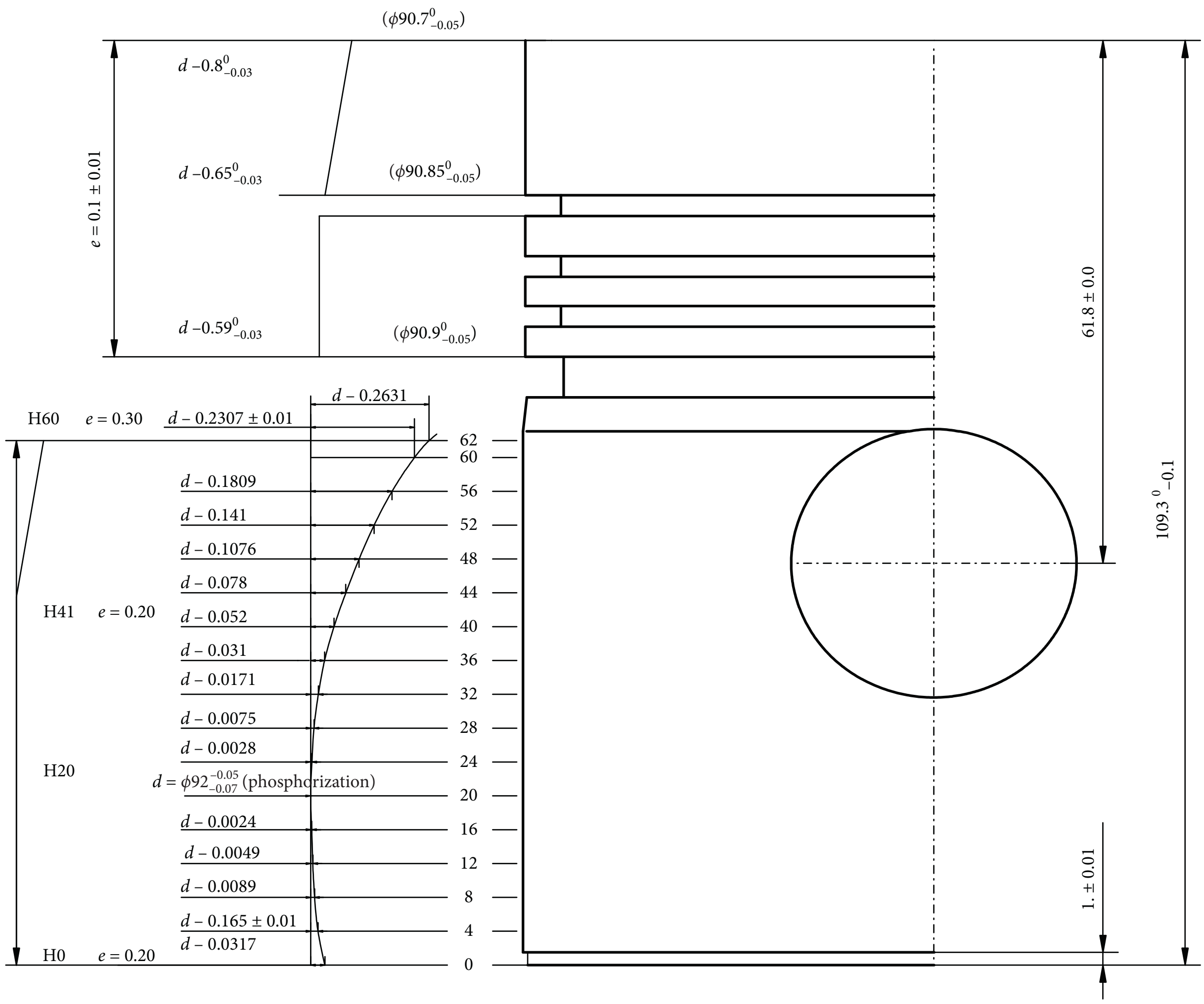

Figure 1: Geometric parameters of the Perkins 240 piston skirt.

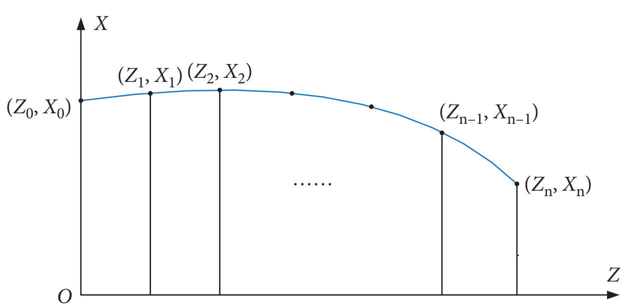

Figure 2: Fitting of discrete points of middle-convex profile in piston section.

$$\begin{cases} 2M_0 + M_1 = \dfrac{6}{L_1}\left(\dfrac{x_1 - x_0}{L_1} - x_0'\right), \\[2ex] M_{n-1} + 2M_n = \dfrac{6}{L_n}\left(x_n' - \dfrac{x_n - x_{n-1}}{L_n}\right), \\[2ex] U_i + 2M_i + \lambda M_{i+1} = 6\dfrac{\left(x_{i+1} - x_i/L_{i-1}\right) - \left(x_i - x_{i-1}/L_i\right)}{L_i + L_{i+1}}, \end{cases} \tag{8}$$

among which, $L_i = z_i - z_{i-1}$, $\lambda_i = (L_{i+1}/L_i + L_{i+1})$, and $U_i = 1 - \lambda_i$. Solution M_i, tdhe fitting equation $x\ (z)$ of middle-convex profile in piston skirt can be obtained by substitution formula (1).

2.3. Analysis of Processing Process of Middle-Convex and Varying Ellipse Piston Skirt. The structure of CNC piston machine tool is shown in Figure 3. Machine motion consists of workpiece (spindle C-axis) rotary motion, tool holder slider linear motion along the Z-axis (parallel to workpiece rotary axis), tool holder linear motion along the X axis (perpendicular to workpiece rotary axis), and tool holder U-axis reciprocating linear motion (control tool high-frequency reciprocating microdisplacement linear motion), X-axis. The cutting depth is controlled by U-axis, and the travel of the tool in high-speed reciprocating linear motion depends on the ellipticity of elliptical cross section at different skirt heights of piston skirt.

The process of turning skirt profile of middle-convex and varying ellipse piston by motion synthesis method can be divided into two independent motions: (1) the motion of tool relative to workpiece forming middle-convex profile is

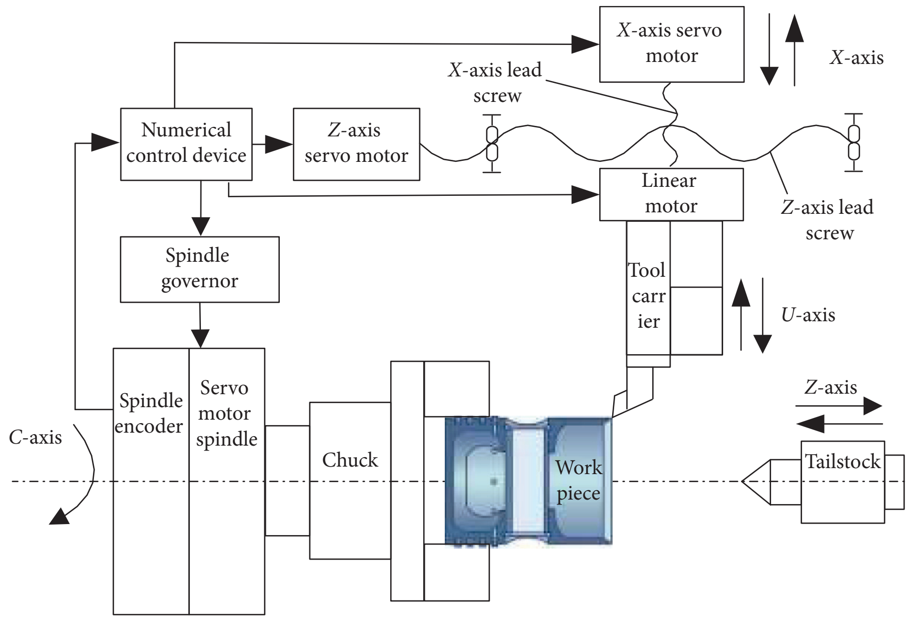

Figure 3: Structure sketch of CNC piston machine tool.

realized by the joint motion of X-axis and Z-axis driven by servo motor; (2) the motion of tool relative to workpiece forming elliptical profile, the reciprocating linear motion of U-axis driven by linear motor, and the motion of spindle.

2.3.1. Middle-Convex Profile Processing. The motion of forming the middle-convex profile is synthesized by the motion of the tool in the piston axis (Z-axis) and the radial direction (X-axis). After the fitting equation of discrete points on the middle-convex profile is obtained, the middle-convex profile is interpolated, and the cubic spline curve is approximated and fitted by micro line segments. According to the requirements of piston skirt surface processing accuracy and tool feed, the number of interpolation points is determined, and the middle-convex profile is interpolated in the piston axis direction. In this paper, the interpolation points are divided by equal interval method. Each step of interpolation, the workpiece rotates one week to complete a micro-short elliptical cylinder processing. Then, the Z-axis position is calculated, and the Z-axis servo motor drives the trawler to the next interpolation point. Figure 4 is a schematic diagram of NC machining of middle-convex profile in piston skirt.

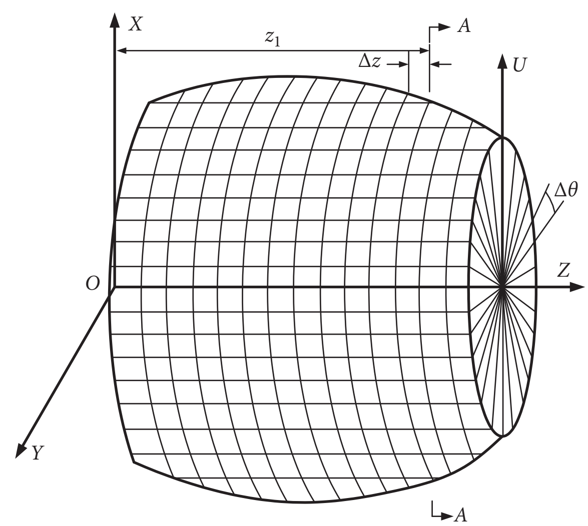

Figure 4: NC machining schematic diagram of middle-convex profile.

2.3.2. Elliptical Profile Processing. The forming motion of the elliptical section of the piston skirt can be decomposed into a high-speed rotational motion of the workpiece and a high-speed reciprocating linear feed motion of the tool in the radial direction of the piston. During the forming process, the piston rotates with the spindle every one revolution, and the tool sequentially processes the long axis of the elliptical section ⟶ the short axis ⟶ the long axis ⟶ the short axis ⟶ the long axis, and the tool feeds twice in rapid reciprocating direction. The higher the spindle speed, the higher the tool feed frequency; the greater the ellipticity of the elliptical section, the greater the turning radius change, the greater the displacement of the tool's fast reciprocating linear feed, and the greater the speed and acceleration of the tool. The key to the elliptical section turning of the piston skirt is the control of the tool path: (1) the high-frequency reciprocating linear motion of the tool; (2) the micro-displacement of the tool reciprocating linear feed motion and the angular displacement of the workpiece high-speed rotation maintain a strict one-to-one correspondence. The schematic diagram of the elliptical section machining process of the piston is shown in Figure 5.

Assuming that the starting position of the tool tip is located at the apex B of the ellipse long axis, the expression of the motion displacement of the tool tip vertex can be described as follows:

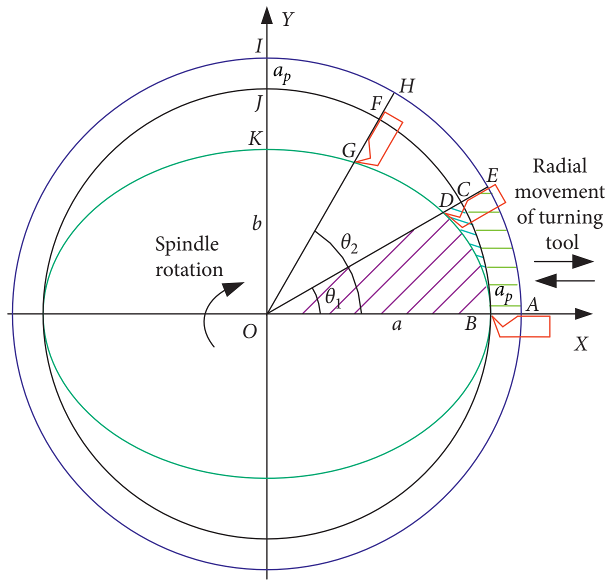

FIGURE 5: Schematic diagram of elliptical section processing.

$$x = a - R = a - \sqrt{a^2\cos^2(2\pi f t) + b^2\sin^2(2\pi f t)}. \quad (9)$$

In the formula, f is the rotation frequency of the lathe spindle and t is time.

When the workpiece rotates with the spindle at a constant speed to turn the piston skirt contour with middle-convex and varying ellipse, the displacement relationship of the four moving axes of the machine tool can be expressed as follows:

$$\begin{cases} C\colon \theta = \dfrac{2\pi n t}{60} = 2\pi f t, \\ Z\colon z = f(t), \\ X\colon x = F(z) = F(f(t)), \\ U\colon u = a - \sqrt{a^2\cos^2(2\pi f t) + b^2\sin^2(2\pi f t)}. \end{cases} \quad (10)$$

This is the NC machining model of the middle-convex and varying ellipse piston skirt in the uniform turning of the workpiece.

2.4. Distribution Law of Cutting Area of Elliptical Section. In the NC machining process of the middle-convex and varying ellipse piston, the rough machining of the piston is completed on an ordinary CNC lathe, and the final forming finishing is completed by a numerical control piston lathe. During the conventional forming and finishing of the piston skirt, the workpiece rotates at a constant speed. The area cut-off in the same elliptical cross section varies with the machining position.

In Figure 5, it is assumed that the cutting depth is changed from the workpiece diameter dimension A of the previous process to the long axis B of the elliptical cross section, and the cutting depth is a_p from 0° to 90°, and the tool is continuously advanced, 90°. When the time is fed to the short axis K of the elliptical cross section, the path of the cutting edge along the surface of the workpiece is substantially like a smooth curve BDGK. During the process of moving the workpiece from 0° to 90°, the area cut by the workpiece through the same corner gradually increases. When the workpiece is turned from 0° to angle, the area to be cut is

$$S_{ABDE} = S_{ABCE} + S_{BOC} - S_{BOD}. \quad (11)$$

In the formula, the elliptical sector area S_{BOD} is calculated as follows:

$$S_{BOD} = \frac{1}{2}ab \cdot \arctan\left(\frac{a}{b}\tan\theta\right). \quad (12)$$

When the workpiece is turned from 1 to 2, the area to be cut is

$$S_{CDGF} = S_{CFHE} + S_{COF} - S_{DOG}. \quad (13)$$

Select the Perkins 240 piston skirt height $H = 20$ elliptical section in Figure 1 (diameter $d = \Phi 92$, corresponding to ellipticity $G = 0.20$). Take the cutting depth $a_p = 0.1$. Calculate the workpiece in the first quadrant every revolution. The depth of cut a_p and its variation a_p and the area cut within the same corner. The results are shown in Table 1.

It can be seen from Table 1 that in the first quadrant, the cutter starts to cut from the long semiaxis of the elliptical section, and the cutting depth a_p gradually increases as the workpiece rotation angle changes; the amount of change in the cutting depth gradually increases at the beginning of the angle a_p at 45°. The vicinity a_p increases to the maximum value and then gradually decreases; the area cut by the workpiece rotating through the same angle (3°) gradually increases. In the first quadrant, the cutting depth a_p, the cutting depth variation a_p, and the change trend of the cutting area in the workpiece rotating through the same angle (3°) are shown in Figures 6–8, respectively.

3. Processing Principle of Equal-Volume Excision Rate

During the process of uniform turning of the elliptical cross section of the middle-convex and varying ellipse piston skirt during uniform turning, the resection area changes periodically with the workpiece rotation angle per unit time, resulting in periodic changes in material removal rate and cutting force, and processing of the piston skirt to some extent. Accuracy has an impact. In order to reduce this effect, this paper proposes the NC machining concept of equal-volume resection rate of middle-convex and varying ellipse piston—the volume ρV of the material removed per unit time is equal during the elliptical cross section of the middle-convex and varying ellipse piston skirt during processing.

The projected area ΔS of the volume ΔV on the elliptical section is

$$\Delta S = \frac{\Delta V}{f}. \quad (14)$$

Table 1: Cutting depth and its variation and the area cut in the same corner.

Angle (°)	a_p (mm)	Δa_p (μm)	Equal-angle cut area (mm^2)
3	0.10027	0.27	0.24134
6	0.10109	0.82	0.24266
9	0.10244	1.35	0.24529
12	0.10432	1.87	0.24919
15	0.10669	2.37	0.25433
18	0.10954	2.85	0.26065
21	0.11283	3.29	0.26807
24	0.11653	3.70	0.27652
27	0.12059	4.06	0.28590
30	0.12498	4.39	0.29611
33	0.12964	4.66	0.30703
36	0.13452	4.88	0.31855
39	0.13958	5.05	0.33054
42	0.14475	5.17	0.34286
45	0.14997	5.23	0.35538
48	0.15520	5.23	0.36797
51	0.16037	5.17	0.38048
54	0.16543	5.06	0.39278
57	0.17031	4.89	0.40473
60	0.17498	4.67	0.41621
63	0.17937	4.39	0.42709
66	0.18344	4.07	0.43724
69	0.18715	3.70	0.44657
72	0.19044	3.30	0.45496
75	0.19329	2.85	0.46233
78	0.19567	2.38	0.46860
81	0.19755	1.88	0.47370
84	0.19891	1.36	0.47758
87	0.19973	0.82	0.48018
90	0.2	0.27	0.48149

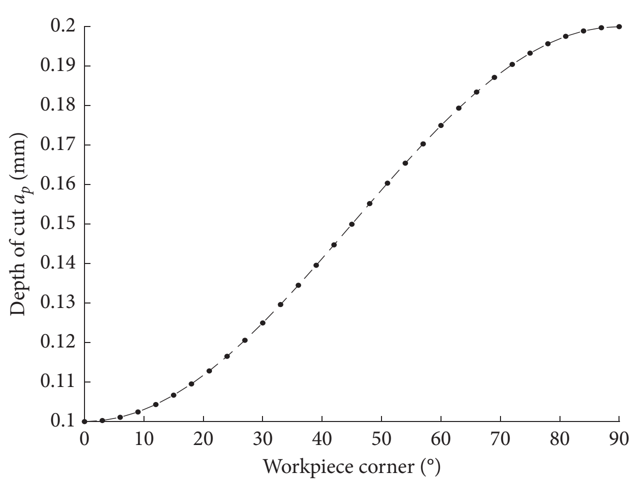

Figure 6: Cutting depth a_p change trend.

The projected area ΔS max of the maximum volume ΔV max allowed to be cut per unit time in the elliptical section is

$$\Delta S_{\max} = \frac{\Delta V_{\max}}{f}. \tag{15}$$

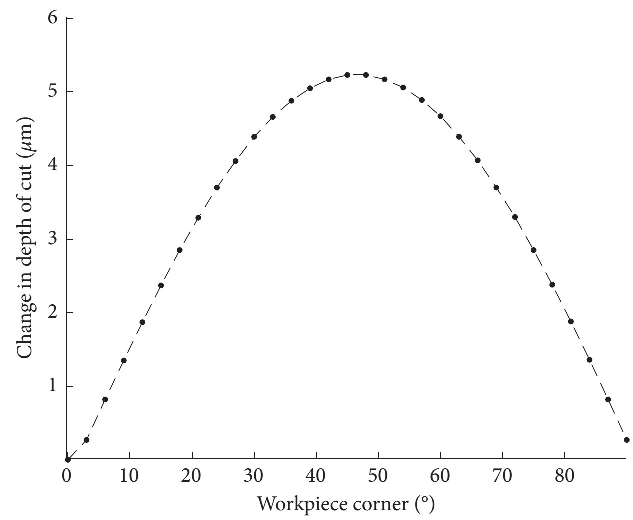

Figure 7: Change in cutting depth a_p change trend.

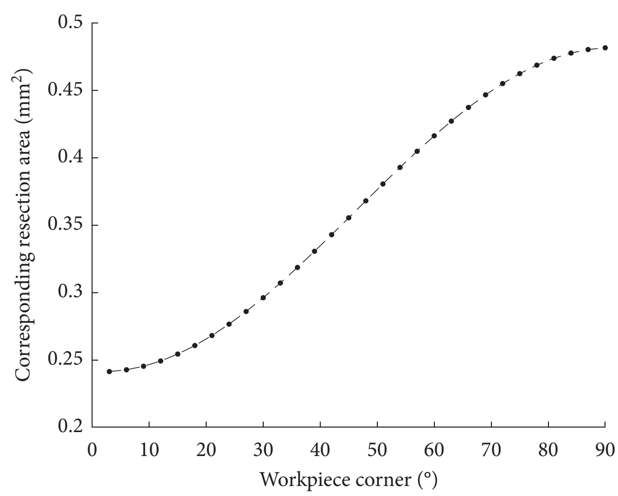

Figure 8: Area cut in the same corner.

In the schematic diagram of the elliptical cross section machining of the middle-convex and varying ellipse piston shown in Figure 4, the total area cut-off in the first quadrant is equal to the difference between the quarter circle area SAOI and the quarter ellipse area SBOK. Then, there is

$$S_{\text{cut}} = S_{AOI} - S_{BOK} = \frac{1}{4}\pi\left(a + a_p\right)^2 - \frac{1}{4}\pi ab. \tag{16}$$

The total area cut out in the first quadrant is divided into n equal parts for processing, so that the time taken to cut each aliquot area ΔS is the same.

$$\Delta S = \frac{S_{\text{cut}}}{n} = \frac{\pi\left[\left(a + a_p\right)^2 - ab\right]}{4n}. \tag{17}$$

In the formula, n must meet the conditions

$$n \geq = \frac{S_{\text{cut}}}{\Delta S_{\max}} = \frac{\pi\left[\left(a + a_p\right)^2 - ab\right]}{4\Delta S_{\max}}. \tag{18}$$

In the first quadrant, the area cut-off from $0 \sim \theta_1, \theta_1 \sim \theta_2, \ldots, \theta_{n-1} \sim \theta_n$ is equal toΔS. Then, there is

$$i\Delta S = \frac{1}{2}\theta_i\left(a + a_p\right)^2 - \frac{1}{2}ab \cdot \arctan\left(\frac{a}{b}\tan\theta_i\right). \tag{19}$$

Combining (17) and (19) gives

$$\frac{i\pi\left[\left(a+a_p\right)^2 - ab\right]}{4n} = \frac{\theta_i\left(a+a_p\right)^2 - ab\cdot \arctan\left((a/b)\tan\theta_i\right)}{2}. \tag{20}$$

Solving the equation yields angle values of $\theta_1, \theta_2, \theta_3, \ldots, \theta_{n-1}, \theta_n$.

When the elliptical section of the middle-convex and varying ellipse piston skirt is machined by the equal-volume resection rate method, the displacement relationship of the four axes of motion of the machine tool can be expressed as follows:

$$\begin{cases} C\colon \theta_i = F\left(i, a, b, a_p\right), \\ Z\colon z = f(t), \\ X\colon x = F(z) = F(f(t)), \\ U\colon u_i = a - \sqrt{a^2\cos^2\theta_i + b^2\sin^2\theta_i}. \end{cases} \tag{21}$$

This is the numerical control machining model when machining the middle-convex and varying ellipse piston skirt in the same volume resection rate method.

4. Equal-Volume Resection Rate Simulation Processing and Experiment

The skirt height H of the middle-convex and varying ellipse piston in Perkins 240 is shown in Figure 1 and its corresponding elliptical cross-sectional long axis value and ellipticity value are shown in Tables 2 and 3, respectively.

According to Table 2, using cubic spline interpolation, the fitting equation and fitting curve of the ellipse long axis value of the Perkins 240 piston skirt can be obtained by MATLAB program fitting (Figure 9).

$$d = 2.73 \times 10^{-3}z - 4.23424 \times 10^{-5}z^2 - 9.93358 \times 10^{-7}z^3 + 91.97066. \tag{22}$$

According to Table 3, using linear interpolation, the equation for the ellipticity of the elliptical section G with the height of the skirt is

$$G = \begin{cases} 0.2, & (0 \le z \le 41), \\ 4.7619 \times 10^{-3}z + 4.7619 \times 10^{-3}, & (41 \le z \le 62). \end{cases} \tag{23}$$

Take the elliptical cross-sectional long axis maximum value plus twice the depth of cut a_p as the cylinder workpiece diameter d_0 before the piston skirt forming process, starting from the skirt height $H = 0$, according to the feed amount $f = 0.001$ [14], calculate the different ellipse values of the long semiaxis a, the ellipticity G, and the short semiaxis b of the section, and calculate the feed of the tool from the skirt height $H = 0$, the tool is cut from $d_0/2$ to the long semiaxis of each different elliptical section. For each different elliptical section, divide the area cut-off in the first quadrant into n equal parts, and obtain the angle corresponding to each aliquot and the corresponding tool feed amount; then, according to the principle of symmetry, the workpiece is rotated within one week. The angle corresponding to each aliquot and the tool feed. Then, the numerical values of workpiece rotation angle and tool feed per equal part are transformed into corresponding NC machining program. According to the NC machining model of equal volume removal rate for middle-convex and varying ellipse piston, the piston skirt can be machined with equal-volume removal rate.

Taking the maximum elliptical section of the Perkins 240 piston as an example, the skirt height $H = 20$, the long axis diameter, the ellipticity $G = 0.20$, the long half axis $a = 46$, the short half-axis $b = 45.9$, and the first quadrant 0-degree cutting allowance $a_p = 0.1$. According to these parameters,

Table 2: Piston skirt height H and corresponding elliptical section long axis value.

Skirt height H (mm)	Long axis (mm)	Skirt height H (mm)	Long axis (mm)
4	91.9835	36	91.969
8	91.9911	40	91.948
12	91.9951	44	91.922
16	91.9976	48	91.8924
20	92	52	91.859
24	91.9972	56	91.8191
28	91.9925	60	91.7693
32	91.9829	62	91.737

Table 3: Piston skirt height H and corresponding cross-sectional ellipticity values.

Skirt height H	Cross-sectional ellipticity
0–41	0.2
41–62	Linear gradient to 0.3

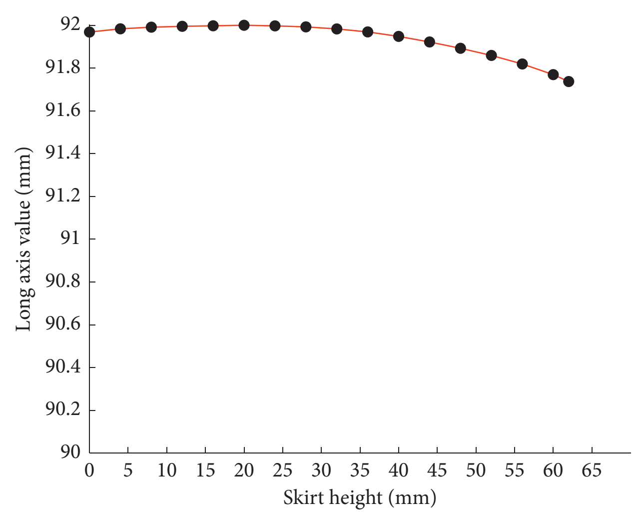

Figure 9: Contour line fitting curve in the Perkins 240 piston skirt.

Table 4: Equal-volume resection rate processing calculation results.

No.	a_p (mm)	Δa_p (μm)	Every aliquot (°)	Actual corner (°)
1	0.1006	0.612	4.4897	4.4897
2	0.1024	1.793	4.4358	8.9255
3	0.1053	2.852	4.3361	13.2617
4	0.1090	3.74	4.2015	17.4632
5	0.1134	4.434	4.0463	21.5094
6	0.1184	4.939	3.8818	25.3912
7	0.1236	5.275	3.7174	29.1085
8	0.1291	5.467	3.5592	32.6678
9	0.1347	5.542	3.4102	36.0780
10	0.1402	5.525	3.2733	39.3513
11	0.1456	5.435	3.1478	42.4991
12	0.1509	5.289	3.0338	45.5330
13	0.1560	5.102	2.9313	48.4642
14	0.1609	4.882	2.8390	51.3032
15	0.1655	4.639	2.7565	54.0597
16	0.1699	4.377	2.6826	56.7423
17	0.1740	4.102	2.6167	59.3590
18	0.1778	3.817	2.5583	61.9173
19	0.1813	3.524	2.5061	64.4234
20	0.1846	3.227	2.4603	66.8837
21	0.1875	2.925	2.4196	69.3033
22	0.1901	2.621	2.3841	71.6873
23	0.1924	2.315	2.3537	74.0410
24	0.1944	2.007	2.3274	76.3684
25	0.1961	1.699	2.3056	78.6740
26	0.1975	1.391	2.2878	80.9618
27	0.1986	1.081	2.2735	83.2353
28	0.1994	0.772	2.2632	85.4985
29	0.1998	0.463	2.2557	87.7542
30	0.2	0.154	2.2458	90.0000

the angle corresponding to the area of each aliquot and the actual rotation angle of the workpiece and the corresponding depth of cut a_p and its variation a_p can be obtained. Take $n = 30$ aliquots, and the calculation results are shown in Table 4.

According to Table 4, when the maximum elliptical cross section of the middle-convex and varying ellipse piston skirt in Perkins 240 is processed by equal-volume resection; in the first quadrant, the change trend of the workpiece turning angle of each aliquot is as shown in Figure 10. The trend of the actual turning angle is shown in Figure 11; the change trend of each cutting area corresponding to the cutting depth is shown in Figure 12, and the corresponding cutting depth is shown in Figure 13.

The obtained actual cutting angle and the tool feed amount corresponding to each aliquot area and the positional parameters of the corresponding X-axis and Z-axis are converted into a numerical control machining program, and the elliptical section of the middle-convex and varying ellipse piston skirt can be obtained. Perform equal-volume resection rate processing. Skirt height $H = 20$ elliptical section first image inner limit equal volume resection rate machine tool motion parameters when middle-convex and varying ellipse piston skirt is processed as shown in Table 5.

According to the machine motion parameters, based on the VERICUT CNC machining simulation platform, the equal-volume resection rate simulation was performed on

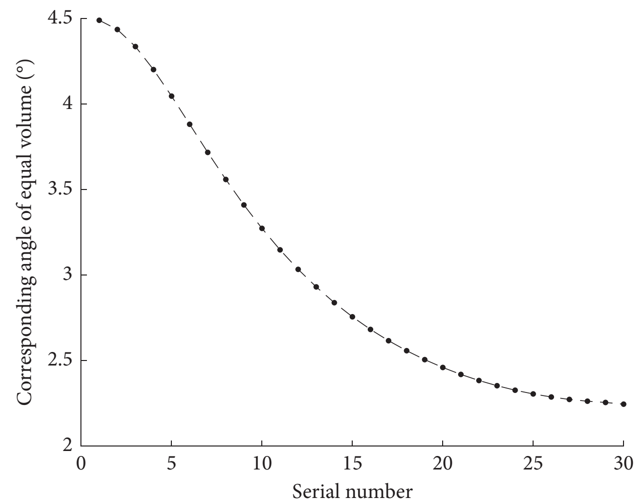

Figure 10: Each resection area corresponds to the workpiece rotation angle.

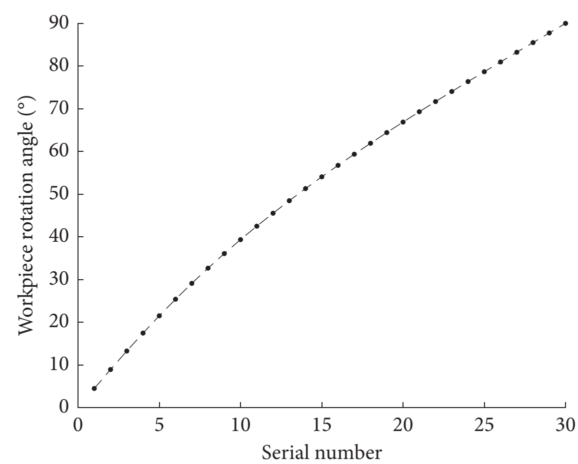

Figure 11: The cut area corresponds to the actual rotation angle of the workpiece.

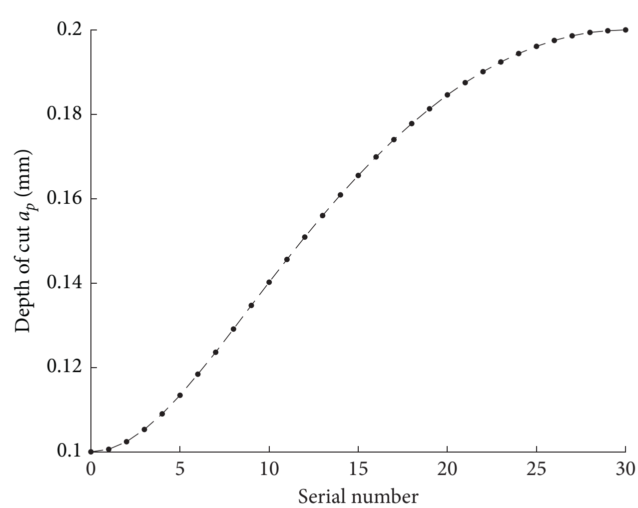

Figure 12: Cut area corresponds to the depth of cut.

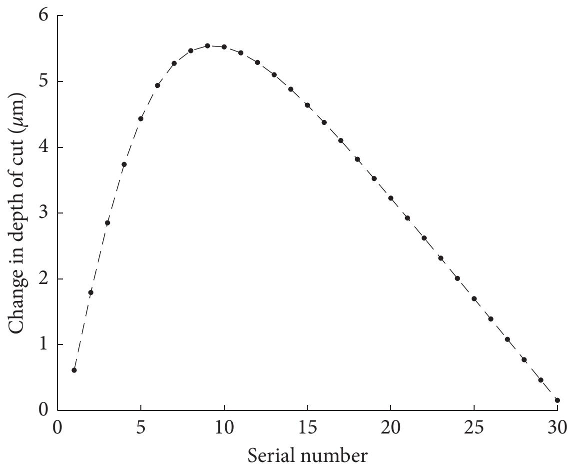

FIGURE 13: Cut area corresponds to the change in the depth of cut.

TABLE 5: Machine tool motion parameters for equal-volume resection rate machining in the first quadrant.

No.	Z (mm)	X (mm)	$\angle C$(°)	U (mm)
N 3310	20.00	46.100	4.4897	0.1006
N 3320	20.00	46.100	8.9256	0.1024
N 3330	20.00	46.100	13.2617	0.1053
N 3340	20.00	46.100	17.4632	0.1090
N 3350	20.00	46.100	21.5094	0.1134
N 3360	20.00	46.100	25.3912	0.1184
N 3370	20.00	46.100	29.1086	0.1236
N 3380	20.00	46.100	32.6678	0.1291
N 3390	20.00	46.100	36.0780	0.1347
N 3400	20.00	46.100	39.3513	0.1402
N 3410	20.00	46.100	42.4991	0.1456
N 3420	20.00	46.100	45.5330	0.1509
N 3430	20.00	46.100	48.4642	0.1560
N 3440	20.00	46.100	51.3032	0.1609
N 3450	20.00	46.100	54.0597	0.1655
N 3460	20.00	46.100	56.7423	0.1699
N 3470	20.00	46.100	59.3590	0.1740
N 3480	20.00	46.100	61.9173	0.1778
N 3490	20.00	46.100	64.4234	0.1813
N 3500	20.00	46.100	66.8837	0.1846
N 3510	20.00	46.100	69.3033	0.1875
N 3520	20.00	46.100	71.6873	0.1901
N 3530	20.00	46.100	74.0410	0.1924
N 3540	20.00	46.100	76.3684	0.1944
N 3550	20.00	46.100	78.6740	0.1961
N 3560	20.00	46.100	80.9618	0.1975
N 3570	20.00	46.100	83.2353	0.1986
N 3580	20.00	46.100	85.4985	0.1994
N 3590	20.00	46.100	87.7542	0.1998
N 3600	20.00	46.100	90.0000	0.2000

the Perkins 240 piston skirt in Figure 1 (as shown in Figure 14).

The ellipticity value of the geometric parameters of the middle-convex and varying ellipse piston skirt in Perkins 240 is magnified 30 times, the remaining parameters are unchanged, recalculated, and simulated, and the simulation processing effect of the middle-convex line and the variable elliptic section can be clearly seen (as shown in Figure 15).

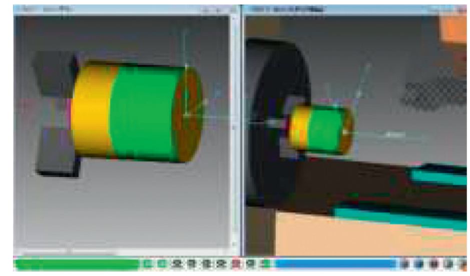

FIGURE 14: Perkins 240 piston skirt equal volume resection rate simulation processing.

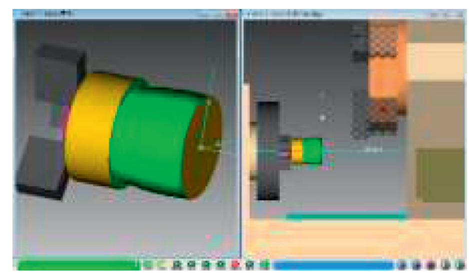

FIGURE 15: Perkins 240 piston skirt ovality magnification 30 times simulation processing.

FIGURE 16: The experimental process of the Perkins 240 piston skirt.

The simulation processing of Perkins 240 piston meets the functional verification requirements of the middle-convex and varying ellipse piston machine. The results show that the simulation machining can simulate the actual machining process of the medium-convex elliptical piston machine tool and also verify the volume of the middle-convex and varying ellipse piston skirt.

By the maximum speed 2500 r/min of the workpiece and the feed rate 0.001 mm/r, the equal-volume cutting rate machining test was carried out on Perkins 240 piston based on the middle-convex and varying ellipse piston NC machining test platform. The machining test results show that the simulation can meet the requirements of the actual machining process of the medium-convex elliptical piston machine tool, and the method is feasible. The experimental process is shown in Figure 16.

5. Conclusion

This paper analyzes the forming principle of the oval section profile of the middle-convex and varying ellipse piston skirt.

The middle-convex profile and ellipse profile of the middle-convex and varying ellipse piston are described mathematically, and the NC machining model of turning piston skirt is established. The distribution of the cutting area in the process of the ellipse section is analyzed. The numerical control machining model of equal-volume cutting rate for middle-convex and varying ellipse piston is established, and the machining method of equal volume cutting rate for middle-convex and varying ellipse piston is verified by simulation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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