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ORIGINAL ARTICLE

A profile error compensation method in precision grinding of screw rotors

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Abstract

In the operation of positive displacement screw machine, the profile accuracy of the screw rotor has a significant effect on the meshing stability between male rotor and female rotor, which is the main factor for vibration, noise, sealing, and wear resistance. This sets extremely strict requirements of the profile accuracy of screw rotor. Therefore, in order to obtain precise screw rotor profile, form grinding is generally used as a finishing process in the manufacture of screw rotors. Unfortunately, the grinding wheel has to be frequently dressed due to inevitable grinding wheel wear. This will cause a substantial waste of time and thus lead to inefficiency. It is therefore desirable to be able to predict the profile error caused by grinding wheel wear in order to make it controllable. In this paper, the influence of installation angle, center distance, and grinding wheel wear on rotor profile error is investigated. A novel method has been proposed for prediction profile error of the screw rotor in precision form grinding. The proposed method has been employed to compensate profile error caused by grinding wheel wear and improve grinding efficiency. Verification experiments were conducted with several screw rotors produced and profile error measured. The comparison shows that the compensation results agree well with the numerical simulation results, showing the effectiveness of the proposed compensation method.

Keywords Screw rotor · Form grinding · Profile error · Compensation method

Nomenclature

$O-X_cY_cZ_c$	Coordinate system of grinding wheel
$O-XYZ$	Coordinate system of screw rotor
R_t, ϕ	Parameter variable of grinding wheel
$\overrightarrow{R}$	Vector form of grinding wheel
M	Contact point between grinding wheel and screw rotor
$\overrightarrow{r}$	Vector form of screw rotor
$\overrightarrow{n}$	General expression for normal vector of contact point
p	Screw parameter of rotor
S	Lead length of screw rotor
T	Distance between the axis of rotor and grinding wheel
ω	Mounting angle of the axes of grinding wheel and rotor
C_i	Points of the machined rotor profile
D_j	Points of the theory rotor profile
E_i	Normal profile error between machined profile and theoretical profile
Δ_T	Center distance error
Δ_ω	Installation angle error
Δ_E	Grinding wheel wear error
d_{gavg}	Mean grain diameter

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1 Introduction

Screw rotors with complex helical profiles have been widely used in positive displacement screw machines, such as screw pump, screw compressor, screw vacuum pump, and screw expander [1]. As the core component of positive displacement screw machines, the profile accuracy of screw rotor plays a critical role in determining the overall performance of screw machines. For example, a three-screw pump consists of one male rotor and two female rotors; during pump rotating, the male rotor drives female rotor in the pump casing insert to form the sealed chambers, and the fluid is conveyed axially from pump suction side to discharge side due to the rotating male rotor [2]. Therefore, the rotor is usually subjected to a high load during operation. Unfavorable profile accuracy may cause excessive noise and vibration, sealing, and reduce wear resistance. This leads to extremely strict requirements for the profile accuracy of screw rotor. Therefore, precision form grinding is generally used as a finishing process in the manufacture of screw rotors. Unfortunately, the grinding wheel has to be frequently dressed due to inevitable grinding wheel wear, which will cause a significant waste of time and lead to inefficiency. In order to produce a screw rotor with high quality and productivity, it is desirable to make the profile error predictable based on conditions of grinding wheel wear and installation parameters. This predictability could result in effective precompensation control of the profile error through machining parameter setting. In the existing literature, the prediction of profile error (due to machining) of screw rotor has been extensively studied. However, to the best of authors' knowledge, effective compensation methods have not been proposed to reduce the profile error. In order to develop an effective compensation method, it is essential to investigate the meshing principle of forming grinding and identify the error sources of screw rotor profile.

In terms of meshing principle of forming grinding and theoretical mathematical modeling of the tool profile design, Litvin et al. [3] applied the enveloping method proposed by Euler in the eighteenth century to the design and manufacturing of gears in 1956. After nearly 30 years of development, Deng et al. [4] used the envelope theory to design screw rotor profile, which included assembly center distance adjustment method, machining correction method, and theoretical profile correction method. Their work provides some reference for the follow-up study on the design and manufacturing of screw rotor. Wu [5] further studied the mesh principle and the enveloping theory, and deduced the contact equation between screw rotor and form cutter. These studies reviewed methods used in form machining of screw rotor in detail, but control method of profile accuracy of screw rotor was not given. Tang et al. [6] proposed a new design method (form-position geometric method) for screw forming cutter based on discrete point tooth according to the existing gear meshing principle in the enveloping structure with stable contact, and overcame the key technical difficulty of traditional meshing theory. This method avoided the solution to the derivatives at each discrete point when solving the equation of contact line by gear meshing theory, and solved the accurate design problem of the cutter at the cusp of the screw profile. Li [7] proposed a novel calculation process based on the groove machining principle to compute the wheel profile with known groove model and wheel axis setting conditions. Further, Jia [8] developed a concise approach on calculation of reasonable orientation and position of grinding wheel for helical groove machining, and optimal selection of installation parameters was also discussed accordingly. The aforementioned studies can provide design methods of forming tool. However, research on the profile error of screw rotor in the process of form grinding has not been reported.

In terms of profile accuracy and error of screw rotor, Stosic [9] proposed a method for calculating milling tool wear amount in screw rotor machining. He considered that different relative motions between each point of tool and screw rotor during the cutting process would result in different tool wear. On this basis, it was shown how to produce a roughing tool that results in semi-finished stock of variable thickness so that it enables the finishing tool to wear at a uniform rate and decreases profile error. The electroplated CBN grinding wheel was firstly introduced to grind screw rotors by Wei et al. [10]. The experimental results showed that it was feasible to grind screw rotors, and grinding quality and efficiency were improved to a certain extent. However, the electroplated CBN grinding wheel was very expensive and cannot be easily dressed. As a result, it has not been widely used in screw rotor precision grinding. Wu et al. [11] used cubic splines to fit discrete point data of the screw rotor profile with clearance and produce the grinding wheel profile. The relationship between motion parameters and profile error of screw rotor was also simulated. Tao et al. [12] proposed a numerical method for evaluating effects of installation errors of grinding wheel on rotor profile including installation angle error, center distance error, and axial position error, but they have not taken measure to compensate profile error. Zhao et al. [13, 14] conducted a lot of research work on form grinding of screw rotor, which involved precision grinding of screw rotors using CNC method. A grinding wheel CNC segmentation dressing method has been proposed to improve the precision of screw rotor grinding. Grinding experiments were performed and correctness of the evaluated results was verified. They attempted to control installation errors and motion parameter so that the target for improving machining accuracy could be reached. Other scholars have also studied the machining of helical surface [15, 16]. In summary, these models can provide acceptable improvement of profile accuracy in screw rotor machining. However, grinding wheel wear (detailed introduction for the grinding wheel wear is given in Section 5.1 Experiment set-up) is unavoidable in grinding process; grinding wheel dressing time will occupy a large part of the whole grinding process. Regrettably, none of them can be used to compensate the profile error of screw rotor due to grinding wheel wear in precision grinding process. In order to prolong the grinding time of newly dressed wheel and improve the grinding efficiency, the profile error caused by grinding wheel wear should be compensated.

In this paper, a novel profile error compensation method is proposed, in order to reduce grinding wheel dressing time and improve the profile precision of screw rotor. This paper is organized as follows. Firstly, the principle of forming grinding and the definition of the profile error are introduced, which gives a basis of the following procedures. Then, the numerical relationship between profile error and grinding parameters (installation parameters and grinding wheel wear) are provided. Subsequently, the proposed profile error compensation method is developed to compensate the profile error caused by the grinding wheel wear. Finally, grinding experiments are conducted on the profile grinding machine, and machined profiles are analyzed through comparison with theoretical profile to demonstrate the effectiveness of the proposed method.

2 Theoretical background

In order to obtain the numerical relationship between profile error and grinding parameters (installation parameters and grinding wheel wear), the screw rotor profile generation model needs to be established according to grinding wheel-screw rotor coordinate transformation and engagement theory.

During the process of grinding, the screw surface is generated through meshing motion between the grinding wheel and screw rotor. Given the shaft section of the grinding wheel is composed of multiple discrete points (Z_c, R_t), the revolution surface equation of grinding wheel can be expressed as follows [5]:

$$\begin{cases} X_c = R_t\cos\phi \\ Y_c = R_t\sin\phi \\ Z_c = f(R_t) \end{cases} \quad (1)$$

where X_c, Y_c, and Z_c are revolution surface equation of grinding wheel; R_t is the radius when the width of the grinding wheel is Z_c; ϕ is the parameter variable that is angle between R_t and $X_cO_cZ_c$ plane; X_c to Y_c direction is defined as positive direction, as shown in Fig. 1. Then, Eq. (1) can be rewritten in vector form as:

$$\overrightarrow{R} = (X_c(R_t,\phi), Y_c(R_t,\phi), Z_c(R_t,\phi))$$

The axes of the grinding wheel and the screw rotor are crossed, forming a mounting angle ω. T is the distance between the axes of the screw rotor and the grinding wheel. The point M is a point on the contact line between grinding wheel and screw rotor. $O-XYZ$ is the screw rotor coordinate system; $O-X_cY_cZ_c$ is the grinding wheel coordinate system, as shown in Fig. 2. The contact line equation can be expressed as [5]:

$$\left(\overrightarrow{k} \times \overrightarrow{r} + p\overrightarrow{k}\right)\bullet\overrightarrow{n} = 0 \quad (2)$$

where p is the screw parameter of rotor calculated by $p = S/2\pi$; S is the lead of the screw rotor; $\overrightarrow{r}$ is the vector $\overrightarrow{OM}$ in the screw rotor coordinate systems $O-XYZ$; $\overrightarrow{k}$ is the unit vector in the Z axis of the screw rotor coordinate system $O-XYZ$; and $\overrightarrow{n}$ is the normal vector of contact point M.

In the grinding wheel coordinate system $O-X_cY_cZ_c$, the vector $\overrightarrow{r}$ can be expressed:

$$\overrightarrow{r} = \overrightarrow{R} + T\overrightarrow{j}_c = R_t\cos\phi\,\overrightarrow{i}_c + R_t\sin\phi\,\overrightarrow{j}_c + f(R_t)\overrightarrow{k}_c + T\overrightarrow{j}_c \quad (3)$$

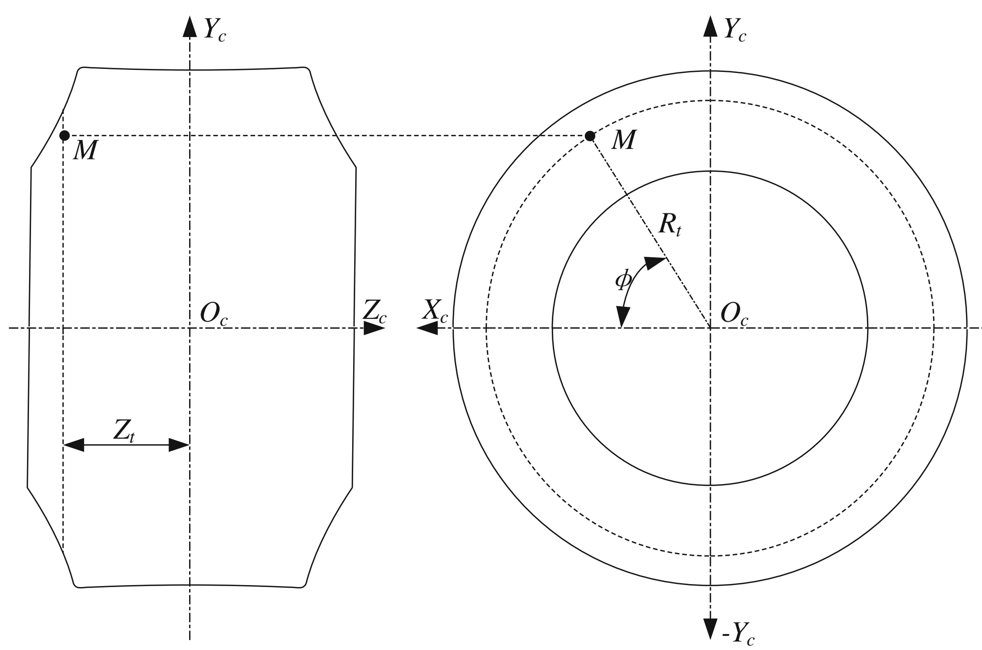


Fig. 1 Schematic diagram of grinding wheel structure

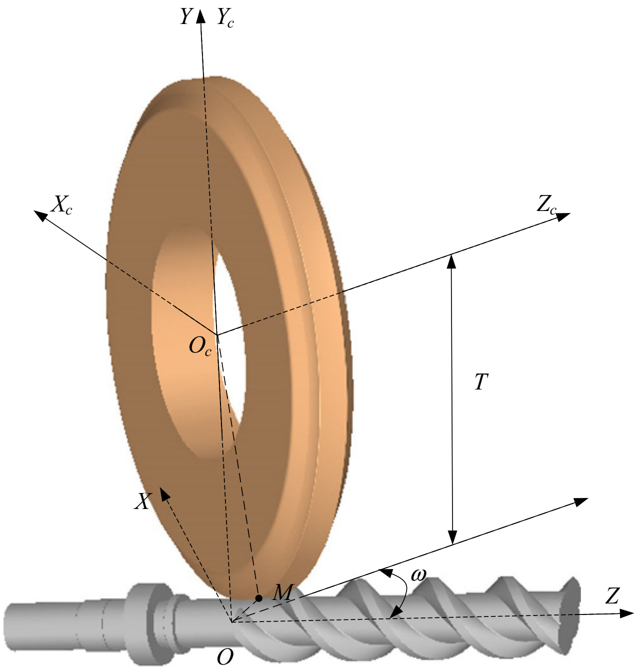


Fig. 2 Coordinate systems of grinding wheel and screw rotor

where $\vec{i}_c$, $\vec{j}_c$, and $\vec{k}_c$ are the unit vectors in the grinding wheel coordinate system $O-X_cY_cZ_c$; $\vec{i}$, $\vec{j}$, and $\vec{k}$ are the unit vectors in the screw rotor coordinate system $O-XYZ$.

Figure 2 shows the geometry relationship between grinding wheel coordinate system $O-X_cY_cZ_c$ and screw rotor coordinate system $O-XYZ$.

$$\begin{cases} X = X_c\cos\omega + Z_c\sin\omega \\ Y = Y_c + T \\ Z = Z_c\cos\omega - X_c\sin\omega \end{cases} \tag{4}$$

$$\begin{cases} \vec{i}_c = \cos\omega\,\vec{i} - \sin\omega\,\vec{k} \\ \vec{j}_c = \vec{j} \\ \vec{k}_c = \cos\omega\,\vec{k} + \sin\omega\,\vec{i} \end{cases} \tag{5}$$

Substituting Eq. (5) into Eq. (3), the vector $\vec{r}$ can be expressed in the screw rotor coordinate system $O-XYZ$:

$$\vec{r} = [R_t\cos\phi\cos\omega + f(R_t)\sin\omega]\vec{i} + (R_t\sin\phi + T)\vec{j} + [f(R_t)\cos\omega - R_t\cos\phi\sin\omega]\vec{k} \tag{6}$$

The term $\vec{k} \times \vec{r} + p\vec{k}$ can be calculated as follows:

$$\vec{k} \times \vec{r} + p\vec{k} = [R_t\cos\phi\cos\omega + f(R_t)\sin\omega]\vec{j} - (R_t\sin\phi + T)\vec{i} + p\vec{k} \tag{7}$$

The component of the normal vector $\vec{n}$ at three coordinate axes can be calculated based on the following equation:

$$\vec{n} = \frac{\partial\vec{r}}{\partial R_t} \times \frac{\partial\vec{r}}{\partial\phi} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \frac{\partial X}{\partial R_t} & \frac{\partial Y}{\partial R_t} & \frac{\partial Z}{\partial R_t} \\ \frac{\partial X}{\partial\phi} & \frac{\partial Y}{\partial\phi} & \frac{\partial Z}{\partial\phi} \end{vmatrix} \tag{8}$$

By taking the partial derivative of each item in Eq. (4), namely, R_t and Z_c, the following equation can be established:

$$\begin{cases} \frac{\partial X}{\partial R_t} = \cos\phi\cos\omega + f'(R_t)\sin\omega \\ \frac{\partial Y}{\partial R_t} = \sin\phi \\ \frac{\partial Z}{\partial R_t} = f'(R_t)\cos\omega - \cos\phi\sin\omega \end{cases} \tag{9}$$

$$\begin{cases} \frac{\partial X}{\partial\phi} = -R_t\sin\phi\cos\omega \\ \frac{\partial Y}{\partial\phi} = R_t\cos\phi \\ \frac{\partial Z}{\partial\phi} = R_t\sin\phi\sin\omega \end{cases} \tag{10}$$

Substituting Eqs. (9) and (10) into Eq. (8) yields the following:

$$\begin{cases} n_x = R_t\sin\omega - f'(R_t)\cos\omega R_t\cos\phi \\ n_y = -f'(R_t)R_t\sin\phi \\ n_z = R_t\cos\omega + f'(R_t)\sin\omega R_t\cos\phi \end{cases} \tag{11}$$

Substituting Eqs. (7) and (11) into Eq. (2) yields the following:

$$(T + p\tan\omega)\cos\phi - \left[f(R_t) + \frac{1}{f'(R_t)}R_t\right]\tan\omega\sin\phi + \frac{1}{f'(R_t)}(p - T\tan\omega) = 0 \tag{12}$$

where $f'(R_t)$ is first-order derivative of the Z_c versus R_t. Since each R_t can deduce two different values of Z_c, it can be regarded as a function of Z_c, as shown in Fig. 1. The term $1/f'(R_t)$ is given by the inverse function theorem.

$$\frac{1}{f'(R_t)} = \left[f^{-1}(Z_c)\right]' \tag{13}$$

According to Eq. (12), we can see that the angle ϕ is the only unknown variable, and it can be calculated depending on T, ω, and the profile parameters of grinding wheel. Thus, the space contact line can be obtained, and the profile of screw rotor section can be solved.

3 Numerical simulation of the grinding processes

3.1 Calculation method for profile error

The rotor profile error must be defined reasonably and scientifically as well as easily measured for evaluating the profile error of screw rotor. Taking a male screw rotor of a certain type of three-screw pump for example, the profiles are designed with arc segments (root) and cycloid segments (side) as shown in Fig. 3. Rotor profile error can be obtained by comparing the machined rotor profile with the theoretical rotor profile as shown in Fig. 4. The coordinates of point C_i are denoted by (x_i, y_i) $(i = \{1, 2, ..., m\})$, where m is the number of data points of machined rotor profile determined by measuring instrument. The coordinates of point D_j are denoted by (x_j, y_j) $(j = \{1, 2, ..., n\})$, where n is the number of data points of the theoretical rotor profile determined by design precision. The shortest distance between the point C_i and the theoretical rotor profile can be defined as profile error at point C_i, which is represented as E_i. When the point C_i is outside the theoretical rotor profile, the profile error E_i is positive; otherwise, it is negative.

For the convenience of calculation, the theoretical rotor profile can be fitted by cubic parameter splines in MATLAB as follows:

$$y = S(x) \tag{14}$$

The profile error between the machined profile and the theoretical profile at point C_i can be calculated as follows:

$$E_i = \pm L_i(min)$$
$$L_i(min) = \sqrt{(x_i - x_k)^2 + (y_i - S(x_k))^2} \tag{15}$$

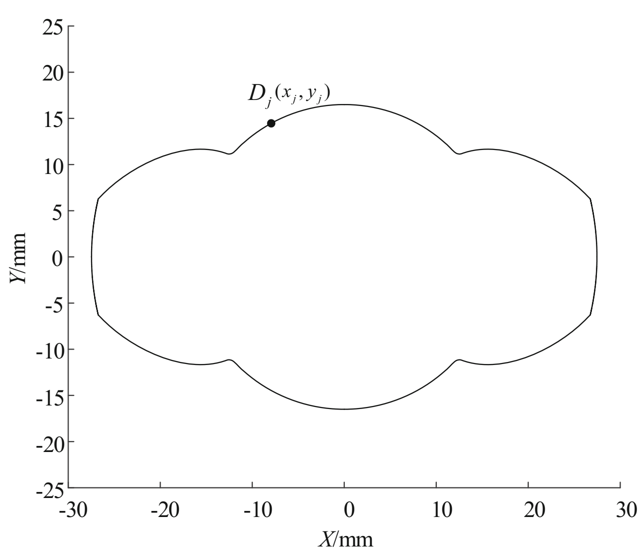


Fig. 3 Theoretical rotor profile

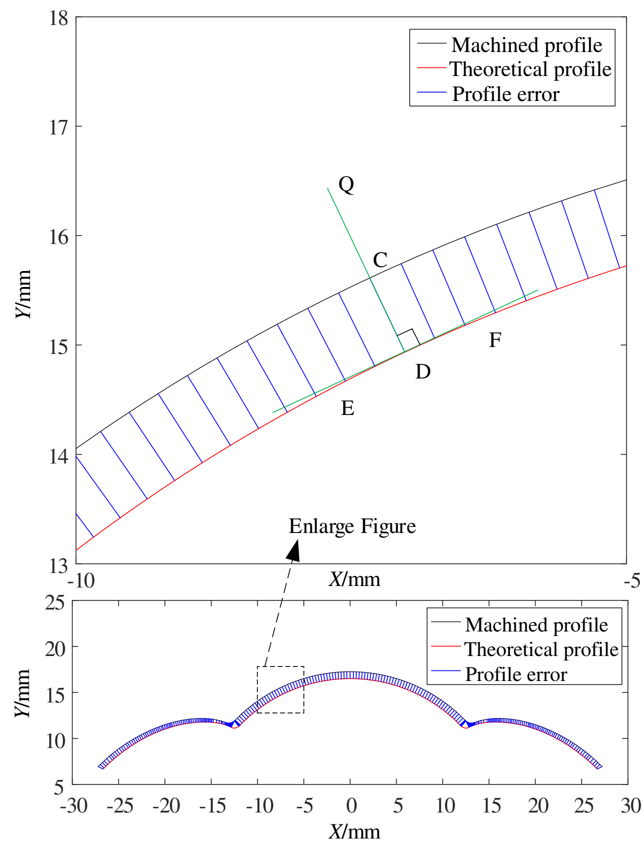


Fig. 4 The profile error of screw rotor cross-section

where the points $(x_k, S(x_k))$ satisfy the Eq. (14). If $y_i > S(x_k)$ "+" is chosen, meaning the machined rotor profile is larger compared with the theoretical rotor profile; otherwise, "-" is chosen. The shortest distance, $L_i(min)$, can be easily solved by MATLAB. Then, the profile error at any point on the machined profile can be easily obtained.

In order to evaluate the effect of center distance, installation angle, and grinding wheel wear on profile error, grinding simulation should be carried out. The wear process of grinding wheel is too complicated to analyze directly. For simplification, the grinding wheel wear value can be assumed to be uniform. The parameters of simulation in grinding are listed in Table 1. Number 1 is the ideal installation parameter and the grinding wheel is in good condition. Numbers 2–13 are different installation parameters and their corresponding grinding wheel wear values.

The effects of center distance, installation angle, and grinding wheel wear value on profile error are presented in Figs. 5, 6, and 7, respectively.

3.2 Influence of center distance on screw rotor profile

Four different center distance errors of grinding wheel (Δ_T) are investigated as listed in Table 1, i.e., − 0.02, −

Table 1 Parameters of simulation in grinding

No.	Center distance (mm)	Installation angle (°)	Wear value (mm)
1	191.500	46.170	0.000
2	191.480	46.170	0.000
3	191.490	46.170	0.000
4	191.510	46.170	0.000
5	191.520	46.170	0.000
6	191.500	46.070	0.000
7	191.500	46.120	0.000
8	191.500	46.220	0.000
9	191.500	46.270	0.000
10	191.500	46.170	0.005
11	191.500	46.170	0.010
12	191.500	46.170	0.015
13	191.500	46.170	0.020

0.01, + 0.01, and + 0.02 mm. The actual center distance ($T + \Delta_T$) is imported into Eq. (12). The simulation results of grinding are shown in Fig. 5. The profile error distribution can be observed clearly and visually. The simulation rotor profile will become larger when the actual center distance is larger than the theoretical center distance, and vice versa. It can be clearly seen that the root errors and side errors are different. The profile error is uniform and equal to the center distance deviation in the arc segments (root). In contrast, the profile error increases with the increase of the screw rotor radius in the cycloid segments (side), and the maximum error in the cycloid segments (side) is slightly smaller than the error of the arc segments (root).

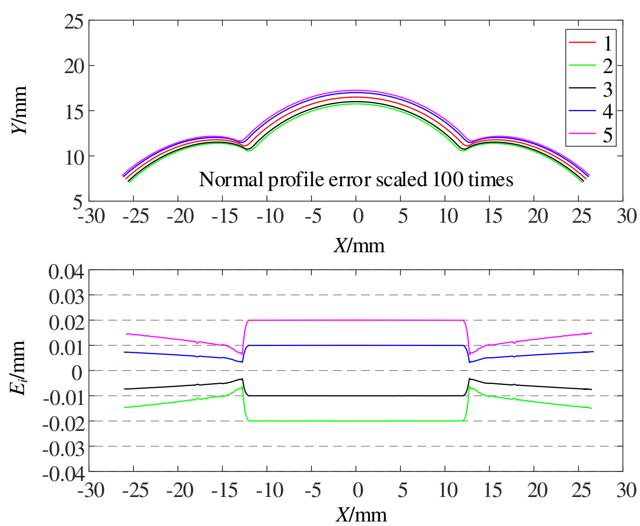


Fig. 5 Effects of center distance error on rotor profile

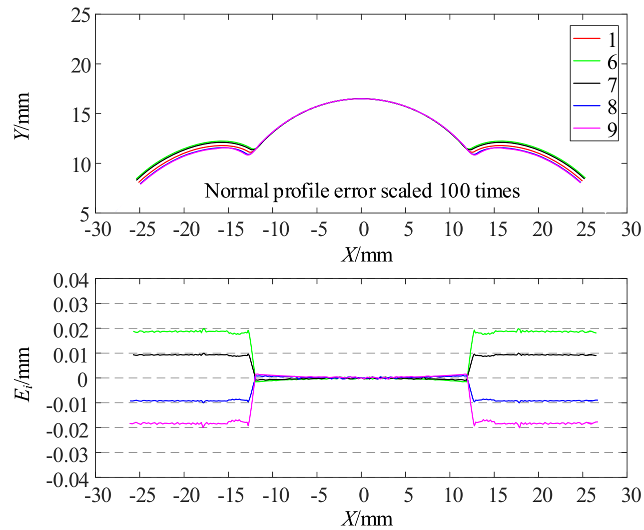


Fig. 6 Effects of installation angle error on rotor profile

3.3 Influence of installation angle on screw rotor profile

Similarly, four different installation angle errors of grinding wheel (Δ_ω) are investigated as listed in Table 1, i.e., respectively, − 0.1°, − 0.05°, + 0.05°, and + 0.1°. Importing the actual installation angle ($\omega + \Delta_\omega$) into Eq. (12), the simulation of grinding is performed with results shown in Fig. 6. As can be observed, the root errors and side errors significantly differentiate from each other, and the profile error is negligible in the arc segments (root). However, the profile error is uniform in the cycloid segments (side), and the simulation rotor profile will become smaller when the actual installation angle is larger.

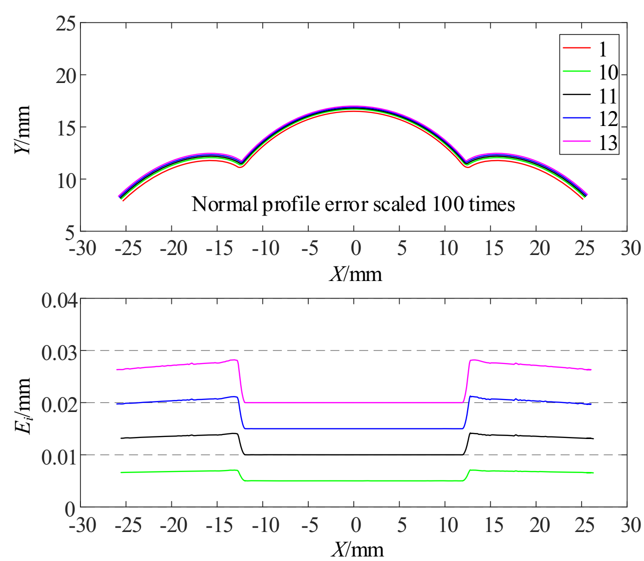


Fig. 7 Effects of grinding wheel wear on rotor profile

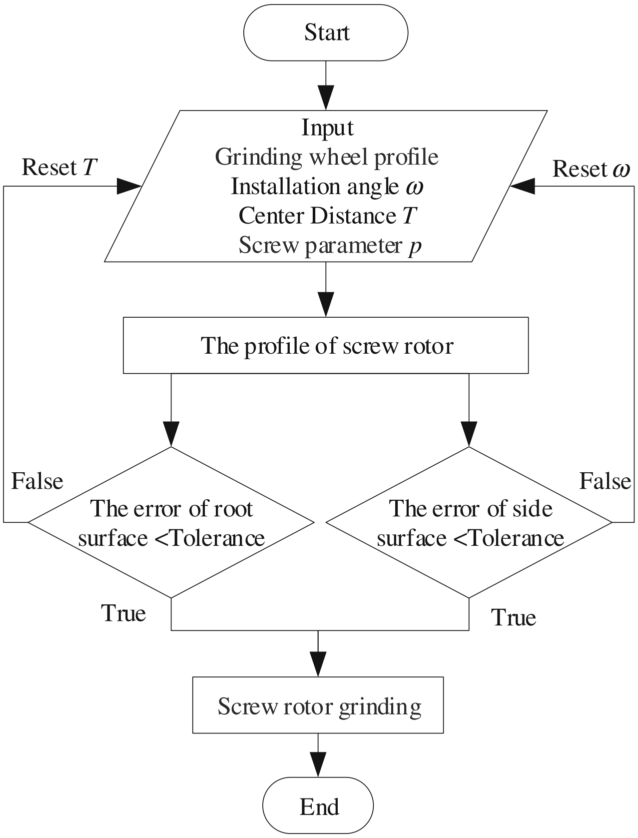


Fig. 8 Profile error compensation procedure

3.4 Influence of grinding wheel wear on screw rotor profile

Four different wear errors of grinding wheel (Δ_E) are investigated as listed in Table 1, i.e., 0.005, 0.01, 0.015, and 0.02 mm. The actual grinding wheel profile shown in Eq. (1) is imported into the Eq. (12). The simulation results of grinding are shown in Fig. 7. As can be seen, the simulation rotor profile will become larger when the actual grinding wheel profile is smaller, and the profile error of cycloid segments (side) is generally larger than the arc segments (root). The profile error is equal to the grinding wheel wear value in the arc segments (root). However, the profile error decreases with the increase of the screw rotor radius in the cycloid segments (side).

Table 2 Parameters of compensation in grinding

No.	Center distance (mm)	Installation angle (°)	Wear value (mm)
10+	191.495	46.190	0.005
11+	191.490	46.210	0.010
12+	191.485	46.230	0.015
13+	191.480	46.250	0.020

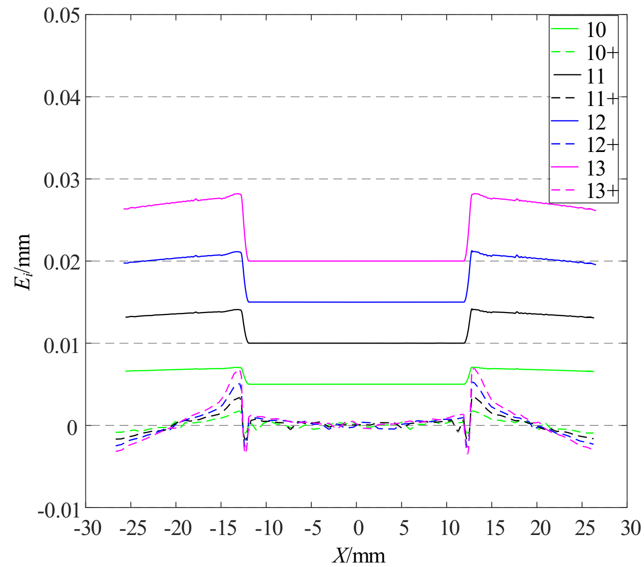


Fig. 9 Screw rotor profile error compensation

As shown in Fig.5 to Fig. 7, the effects of center distance, installation angle, and grinding wheel wear value on profile error are different. The profile error can be classified into two categories: root errors (arc segments) and side errors (cycloid segments). Grinding wheel wear is inevitable in grinding process of screw rotors. In order to ensure the accuracy of the screw profile, grinding wheel has to be frequently dressed, which will waste a lot of time and lead to inefficiency. In this paper, a novel method is developed to compensate profile error caused by grinding wheel wear. The compensation is achieved by adjusting the center distance and installation angle.

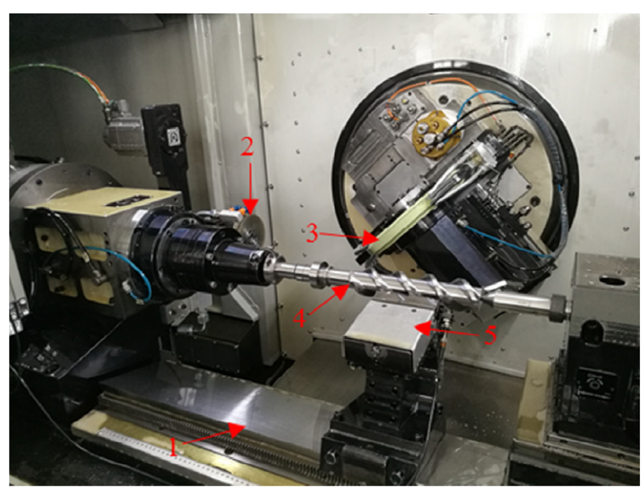


Fig. 10 Grinding experimental setup. (1) Worktable. (2) Diamond dressing wheel. (3) Grinding wheel. (4) Screw rotor. (5) Auxiliary supporting

Table 3 Geometric parameter of the screw rotor

No.	Item	Value
1	Tip diameter (mm)	54.94–54.95
2	Root diameter (mm)	33.00–33.01
3	Lead (mm)	108.00
4	Pitch diameter (mm)	33.00
5	Center distance (mm)	191.50
6	Lead angle (°)	46.17
7	Profile tolerance (mm)	± 0.01
8	Grinding allowance (mm)	0.02
9	Screw direction	Right-handed

4 The method of profile error compensation

In Section 3, the numerical relationships between profile error and center distance, installation angle, and grinding wheel wear value are demonstrated clearly. Because of wear, the grinding wheel has to be dressed after two times grinding in industrial applications. In order to reduce the dressing times and improve machining efficiency, the center distance and installation angle can be adjusted in the grinding process. The diagram of the screw rotor grinding process is shown in Fig. 8. The parameters of compensation in grinding are listed in Table 2.

Four different wear values (Δ_E) are investigated as listed in Table 2, i.e., 0.005, 0.01, 0.015, and 0.02 mm; the corresponding center distance and installation angle are also listed in Table 2. The actual center distance, installation angle, and actual grinding wheel profile are imported into Eq. (12). The simulation rotor profile can be presented as shown in Fig. 9. As can be seen, the simulation rotor profile error is significantly lower than results with no compensation. The root errors can be almost completely compensated, and the side errors can be controlled within the tolerance band. However, due to the complexity of the grinding wheel surface, the wear value is difficult to measure accurately and directly. Considering that the rotor profile error can be easily measured, the experiments are designed to reverse the grinding wheel wear through the rotor profile error, and provide numerical basis for compensation.

Table 4 Installation parameters

No.	Center distance (mm)	Installation angle (°)
M1	191.500	46.170
M2	191.500	46.170
M3	191.500	46.170
M4	191.500	46.170

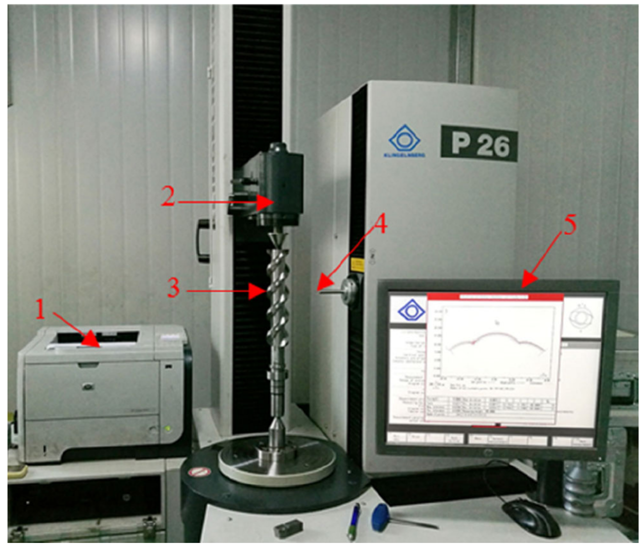


Fig. 11 The fully automatic CNC-controlled P 26 precision measuring center. (1) Printing mechanism. (2) Clamping device. (3) Screw rotor. (4) Measuring head. (5) Display instrument

5 Experiment and validation

5.1 Experiment setup

In screw rotor precision grinding, the grinding wheel needs to be dressed after every screw rotor is ground, thus leading to inefficiency. In order to validate the proposed model in this work, two groups of screw rotor grinding experiments are conducted on SU G500H profile grinding machine using an alumina grinding wheel (NORTON-3NQ60-H12VSP). The screw rotor was Y40Mn (HB 190). As a slender rod, the slenderness indexes of the screw rotor at the root diameter and top diameter are 12.12 and 7.28 (the length of screw rotor L = 400 mm), respectively. The presence of force and motion may

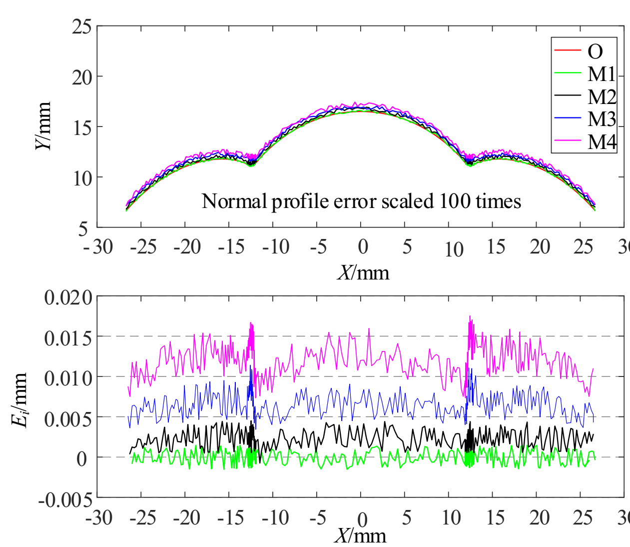


Fig. 12 Profile error of the first group

Table 5 Compensation parameters

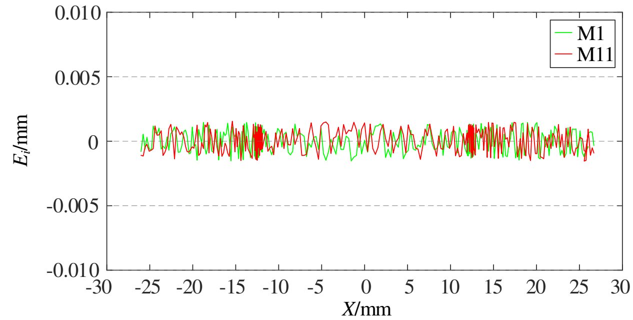
No.	Center distance mm (mm)	Installation angle (°)	Wear value (mm)
M11	191.500	46.170	0.000
M22	191.498	46.180	0.002
M33	191.493	46.210	0.007
M44	191.487	46.240	0.013

lead to deformation and vibration of the screw rotor during grinding. To avoid potential vibration and deformation, an auxiliary support is used in this experiment, as shown in Fig. 10 ((5) Auxiliary supporting). Variocut G600HC was used as cutting fluid in the grinding process. The geometric parameters of the screw rotor are shown in Table 3. The installation parameters are shown in Table 4. In the first group of experiments, the grinding wheel continuously ground two screw rotors with four helical grooves without being dressed. The rotor profile error was measured using the fully automatic CNC-controlled P26 precision measuring center as shown in Fig. 11.

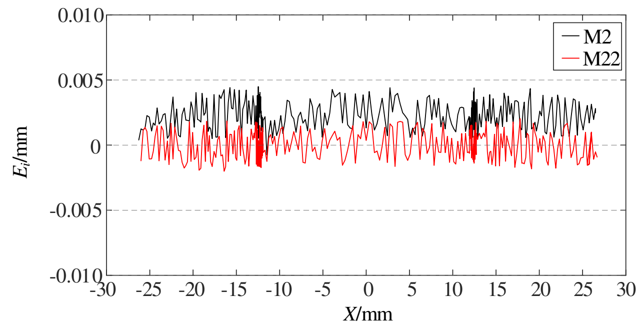
Wear and fracture, or even pull-out of abrasive grits, are unavoidable in the grinding process. In this study, NORTON's grinding wheel is used, and its abrasive grits have good grinding performance. The key characteristic of these high-performance abrasives is the unique combination of hardness and toughness, which is essential for controlling micro-fracturing. At the same time, micro-fracturing of the grains is crucial for providing a continuous supply of sharp cutting edges during grinding [17]. On the other hand, the precision grinding of screw rotors is investigated in this paper. The ratio of grinding depth to abrasive grain diameter is about 0.078 (mean grain diameter $d_{gavg} = 0.255$ mm) [18], which is an extremely small value. Hence, the shear force borne by a single abrasive grain is also very small. Therefore, mainly wear and micro-fracturing occurred under this condition. In this paper, wear and micro-fracture are collectively referred to as grinding wheel wear. Under this assumption, two groups of screw rotor grinding experiments can be carried out.

5.2 Results and discussion

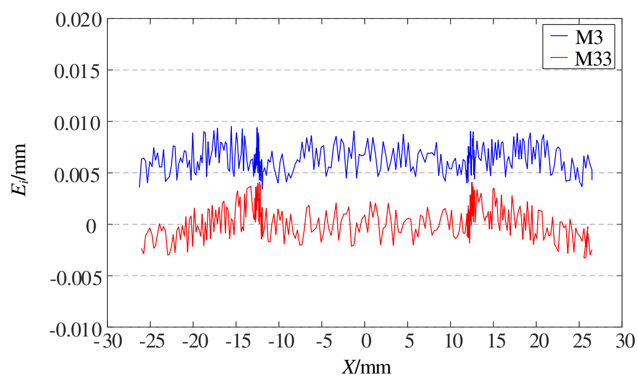
The first group experimental results are shown in Fig. 12. As can be seen from M1–M4, the rotor profile is getting bigger and bigger with the increase of grinding time. This is consistent with above analytical results. In order to obtain precise compensation parameters, the cause of profile error should be fully analyzed. Wear and deformation of grinding wheel occur simultaneously in the practice of grinding, and both will cause the rotor profile error. Nevertheless, in this study, the grinding depth is only 0.02 mm. As such, the normal grinding force is



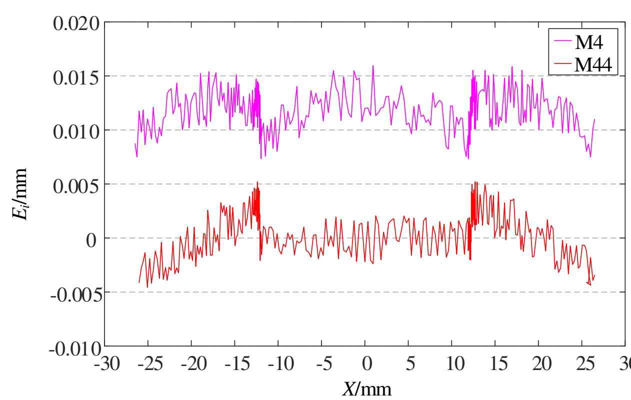
(a) Comparison between M11 and M1



(b) Comparison between M22 and M2



(c) Comparison between M33 and M3



(d) Comparison between M44 and M4

Fig. 13 The result comparison of two group experiments. **a** Comparison between M11 and M1. **b** Comparison between M22 and M2. **c** Comparison between M33 and M3. **d** Comparison between M44 and M4 very small. In addition, NORTON's grinding wheel is used in this research, and its type of bond is vitrified. In this way, this grinding wheel has good stiffness. Based on these two considerations, the grinding wheel deformation can be neglected. Therefore, the cause of profile error can be attributed to the grinding wheel wear. In addition, the results also show that grinding wheel wear is not proportional to grinding time. Instead, it gets faster and faster. Meanwhile, surface integrity becomes worse and worse as grinding time increases. The wear is worst in the transition area between the root and the side of the grinding wheel because of sharp corner. The wear value of grinding wheel can be derived based on screw rotor profile error. The grinding wheel profile error is imported into profile error compensation procedure as shown in Fig. 8. Further, the compensation parameters can be obtained. In Table 5, the wear values and the corresponding compensation parameters are listed.

Figure 13 shows the comparison result between the two groups of experiments. It is clearly shown that the profile error of M11–M44 had been significantly reduced compared with the profile error of M1–M4. The change trend of rotor profile by experiment is consistent with simulated result. This means the simulation analysis of the effects of installation errors and grinding wheel wear on rotor profile in this article is accurate and reliable. Compared with the theoretical profile, the error of each helical groove could be limited to ± 5 μm under conditions of double grinding time within the tolerance band ± 0.01 mm. The comparison shows that the compensation results agree well with the numerical simulation results, showing the effectiveness of the proposed compensation method.

6 Conclusion

This paper proposes a numerical method to evaluate the effects of installation errors and grinding wheel wear on rotor profile, and a novel profile error compensation method has been developed. The screw rotor profile generation model was established based on coordinate transformation and engagement theory. According to the established generation model, detailed numerical simulation was performed. The numerical cases show the effects of center distance, installation angle, and grinding wheel wear on rotor profile are different. The profile error caused by grinding wheel wear can be compensated by adjusting the center distance, installation angle of grinding wheel. Grinding experiments for male rotor by introducing different installation parameters are performed to verify the results of the numerical cases. Some important conclusions are drawn as follows:

1. The screw rotor profile generation model has been established according to grinding wheel-screw rotor coordinate transformation and engagement theory. The contact line equation between screw rotor and grinding wheel is derived, and the effect of center distance, installation angle, and grinding wheel wear on profile error is investigated.
2. The rotor profile error is defined and classified into two categories: root profile error (arc segments) and side profile error (cycloid segments). Error-sensitive factors are identified. Installation angle error is the main cause of side profile error, while center distance error affects both root profile error and side profile error but with different degree.
3. A novel profile error compensation method has been proposed in this paper. A set of male rotor grinding experiments are conducted. Compared with the theoretical profile, the error of each helical groove is limited to ± 5 μm under conditions of double grinding time within the tolerance band ± 0.01 mm.

The above conclusions show that the proposed method is accurate and reliable to compensate profile error caused by grinding wheel wear for a certain screw pump's profile. It can be further used to predict and control the profile error for screw rotor grinding. In the future work, methods for obtaining grinding wheel wear values should be further studied for efficient implementation of this approach in error compensation process. In addition, the quantitative research of the grinding wheel deformation should be carried out during the grinding process. On the other hand, the profile error compensation method should also be considered to be extended into other types of screw profiles. Additionally, the practical compensation software for this approach can be developed to improve the efficiency of error analysis and compensation.

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