Abrasive Particles Trajectory Analysis and Simulation of Cluster Magnetorheological Effect Plane Polishing

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Abstract

Kinematics model of abrasive particles for certain eccentric and linear interpolation swing uncertain eccentric, uncertain eccentricity of X direction and Y direction in plane polishing based on cluster magnetorheological(MR) effect are built and simulated by computer, and also obtain the influence law of key factors such as the speed ratio \(r\) of polishing disk and workpiece, the eccentricity \(e\) to polishing disk, the distance of abrasive particles \(P\) to the center of polishing disk, the ratio \(F\) of swing range \(A\) and swing speed \(V\) to polish quality. At last, polishing experiment for single crystal 6H-SiC is carried out on the experiment equipment of the cluster MR effect by selecting optimized parameters through the simulation results, which verified the correctness of the simulation results.

1. Introduction

With continuous development of optical and microelectronic technology, more and more optical components are used in complex systems related to military, aerospace, electronics and other fields, so improving the ultra-precision machining capacity and seeking for suitable processing methods for optical materials are most critical factors. Magnetorheological(MR) finishing is an advanced optical surface processing technology that combine ferromagnetic science, fluid dynamics, chemical and optical

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processing, which realizing precision polishing with control the movement of abrasives by ferromagnetic particles under magnetic field. Foreign and domestic scholars and researchers have made unremitting study on the technology over the years.

This study proposes a new ultra-smooth surface polishing method that utilizes a cluster distributed magnets to form a polishing tool [1-4]. The principle of it is based on MR effect that mixes abrasives particles in MR fluid, then the abrasive brush based on MR-effect constituted by small size magnets bonding free abrasives together and form polish brush by arraying the cluster multi abrasive brush based on MR-effect, on which surface generates uniformly dispersed abrasive media layer of viscoelastic to control abrasive attitude, particle trajectory, residence time and concentration of abrasive to improve efficiency and accuracy of ultra-smooth polishing. Ultra-smooth polishing based on cluster MR effect diagram is shown in Fig. 1, from which it can be seen that cluster magnets are embedded on polishing disk that made with anti-magnetic material while MR fluid spraying. The workpiece is fixed on the tool head, and polishing tool head and rotates do its own axis and swings within a certain range at the same time.

In the actual polishing process, polished surface quality mainly depends on the abrasive trajectory and force intensity on the workpiece, the more complex trajectory and the trajectory of the more uniform coverage, the better the polishing quality. According to the movement law of ultra-smooth surface polishing based on the cluster MR effect, the kinematic trajectory equation of abrasive on the surface of the workpiece is derived, further study of the polishing speed, workpiece speed, eccentricity, swing speed and amplitude of the variation of abrasive trajectory is conducted by computer simulation. These studies provide a theoretical basis for parameters optimization of ultra-smooth surface polishing based on cluster MR effect and improving the quality of the workpiece surface.

![Ultra-smooth polishing based on cluster MR effect diagram](image)

**Fig. 1** Ultra-smooth polishing based on cluster MR effect diagram

### 2. Kinematic model of abrasive movement trajectory

The effective constraint of MR effect-based chain string on the abrasives makes them in a semi-fixation state to form uniform polishing pad on the polishing disk under MR effect during ultra-precision polishing based on cluster MR effect [5]. In order to facilitate researching and analyzing, the article assumes uniform distribution of abrasive particles and the fixation on magnetic polishing pad and move together with the polishing pad, then take simplified model of a single abrasive particle polishing to conduct the research.

When analyzing the trajectory of the abrasive, the polishing disk and workpiece are simplified into two parts those make relative flat plane motion, coordinate system $XOY$ and $X'OY'$ are established in polish disk center $O$ and workpiece center $O'$ and both axis $OX$ and $OX'$ are along the line $OO'$ while origins of coordinates are $O$ and $O'$. The distance of $OO'$ is defined as eccentricity $e$ while angular velocities of
polish disk and workpiece fixed disk are \( \omega_1, \omega_2 \). Kinematics model of abrasive particles for certain eccentric and linear interpolation swing uncertain eccentric, uncertain eccentricity of \( X \) direction and \( Y \) direction in plane polishing are established (shown in Fig. 2) according to the relationship of coordinate system \( X'OY' \) relative to coordinate system \( XOY \).

2.1. Certain eccentricity polishing

It is defined as certain eccentricity polishing when \( e \) is constant that distance between centers of workpiece and polish disk is constant. As is shown in Fig. 2(a), assume in a transient an abrasive \( P \) that \( r_p \) away from the polish disk center \( O \) just comes into contact with the workpiece that radius is \( r \), initial turning angle \( \varphi \) can be gained according to cosine theorem [6-8]:

\[
\varphi = \arccos \frac{r^2 + e^2 - r_p^2}{2re_p}
\]

The motion equation of point \( P \) on polish disk with coordinate system \( XOY \) is:

\[
\begin{align*}
x_p & = r_p \cos(\omega_1 t + \varphi) \\
y_p & = r_p \sin(\omega_1 t + \varphi)
\end{align*}
\]

The coordinate of workpiece center \( O \) in coordinate \( XOY \) in any transient is:

\[
\begin{align*}
x_o & = e \cos \omega_2 t \\
y_o & = -e \sin \omega_2 t
\end{align*}
\]

Then motion relationship of abrasive particle \( P \) on polish disk with coordinate system \( XOY \) is:

\[
\begin{align*}
x_p' & = r_p \cos(\omega_1 t + \varphi - \omega_2 t) + e \cos \omega_2 t \\
y_p' & = r_p \sin(\omega_1 t + \varphi - \omega_2 t) - e \sin \omega_2 t
\end{align*}
\]

2.2. Linear interpolation swing uncertain eccentric polishing

As is shown in Fig. 2(b), it is defined as linear interpolation swing uncertain eccentric polishing when the workpiece in the axis \( X \) makes linear swing motion to the center of \( O \), the angle between swing trajectory and axis \( X \) is \( \beta \), swing scope is \( A \), swing velocity is \( V \). We assume that distance \( OO' \) is \( e \) and initial turning angle \( \varphi \) is the same as equation (1) showed so that trajectory of abrasive particle \( P \)
is the same as equation (2) showed. Because the workpiece swings along the line that forms angle $\beta$ with the X-axis, the coordinate of workpiece center $O$ in coordinate $X'OY'$ in any transient is:

$$
\begin{align*}
  x_o &= -\frac{A}{2} \sin(2\pi ft) \cos \beta = -\frac{A}{2} \sin(\frac{\pi vt}{A}) \cos \beta \\
  y_o &= -\frac{A}{2} \sin(2\pi ft) \sin \beta = -\frac{A}{2} \sin(\frac{\pi vt}{A}) \sin \beta
\end{align*}
$$

(5)

The trajectory equation of abrasive particle $P$ relative to coordinate system $X'OY'$ can be inferred from theory of equation (4):

$$
\begin{align*}
  x_p &= r_p \cos(\omega t + \phi - \omega_T t) + e \cos \omega_T t + A \sin(\frac{\pi vt}{A}) \cos \beta \\
  y_p &= r_p \sin(\omega t + \phi - \omega_T t) - e \sin \omega_T t + A \sin(\frac{\pi vt}{A}) \sin \beta
\end{align*}
$$

(6)

2.3. Uncertain eccentricity of X direction

As is shown in Fig. 2(c) that it is defined as uncertain eccentricity of $X$ direction when $\beta$ of equation (6) is 0 degree, the workpiece swings to the center $O$ along axis $X$. The trajectory equation of abrasive particle $P$ relative to coordinate system $X'OY'$ is [7-8]:

$$
\begin{align*}
  x_p &= r_p \cos(\omega t + \phi - \omega_T t) + e \cos \omega_T t + A \sin(\frac{\pi vt}{A}) \\
  y_p &= r_p \sin(\omega t + \phi - \omega_T t) - e \sin \omega_T t
\end{align*}
$$

(7)

2.4. Uncertain eccentricity of Y direction

As is shown in Fig. 2(d) that it is defined as uncertain eccentricity of $Y$ direction when $\beta$ of equation (6) is 90 degree, the workpiece swings to the center $O$ along axis $Y$. The trajectory equation of abrasive particle $P$ relative to coordinate system $X'OY'$ is:

$$
\begin{align*}
  x_p &= r_p \cos(\omega t + \phi - \omega_T t) + e \cos \omega_T t \\
  y_p &= r_p \sin(\omega t + \phi - \omega_T t) - e \sin \omega_T t + A \sin(\frac{\pi vt}{A})
\end{align*}
$$

(8)

3. Computer simulation of abrasive particle trajectory

The equation (7) and equation (8) are special cases of equation (6), so trajectory equation of the abrasive particle on workpiece is established according to equation (4) and equation (6), simulation program is done by MATLAB[10] to analyze variation of abrasive particle.

In order to facilitate analyzing, the rotation speed ratio $r$ ($r = \omega_2 / \omega_1$, positive in counterclockwise, negative in clockwise) and eccentricity $e$ of polish disk and workpiece, the distance $r_p$ between abrasive particle $P$ and center $O$ of polish disk, the ratio $F$ ($F = A / 2V$) of swing speed $V$ and swing scope $A$ are set as eigenvalue.
Fig. 3 Certain eccentric polishing trajectory (a) \( r = 1 \), \( e = 62 \), \( r_e = 62 \), \( r_r = 52.5 \) (b) \( r = -4 \), \( e = 62 \), \( r_e = 62 \), \( r_r = 52.5 \) (c) \( r = 4.2 \), \( e = 62 \), \( r_e = 62 \), \( r_r = 52.5 \) (d) \( r = -8.8 \), \( e = 62 \), \( r_e = 62 \), \( r_r = 52.5 \) (e) \( r = -8.8 \), \( e = 62 \), \( r_e = 62 \), \( r_r = 52.5 \) (f) \( r = -8.8 \), \( e = 90 \), \( r_e = 62 \), \( r_r = 52.5 \) (g) \( r = -8.8 \), \( e = 62 \), \( r_e = 30 \), \( r_r = 52.5 \) (h) \( r = -8.8 \), \( e = 62 \), \( r_e = 100 \), \( r_r = 52.5 \)

Fig. 4 Linear interpolation swing uncertain eccentric with \( \beta = 30^\circ \) (a) \( r = 1 \), \( e = 62 \), \( r_e = 62 \), \( F = 0.21 \) (b) \( r = -4 \), \( e = 62 \), \( r_e = 62 \), \( F = 0.21 \) (c) \( r = -8 \), \( e = 62 \), \( r_e = 62 \), \( F = 0.21 \) (d) \( r = -8.8 \), \( e = 62 \), \( r_e = 62 \), \( F = 0.21 \) (e) \( r = -8.8 \), \( e = 62 \), \( r_e = 62 \), \( F = 0.2 \) (f) \( r = -8.8 \), \( e = 92 \), \( r_e = 62 \), \( F = 0.2 \) (g) \( r = -8.8 \), \( e = 62 \), \( r_e = 30 \), \( F = 0.21 \) (h) \( r = -8.8 \), \( e = 62 \), \( r_e = 80 \), \( F = 0.21 \)

3.1. The effect of speed ratio on abrasive particle trajectory

Some laws can be summed up according to analysis of abrasive particle trajectory:

1) It is more complex when speed ratio less than zero than that is greater than zero no matter in certain eccentricity polishing or linear interpolation swing uncertain eccentric polishing, which shows the polishing quality is better when speeds of workpiece and polish disk are in contrary.
2) The sparsest trajectory exists (shown in Fig. 3(a), Fig. 3(b), Fig. 4(a), Fig. 4(b)) when the speed ratio is integer no matter in certain eccentricity polishing or linear interpolation swing uncertain eccentric polishing, which goes against obtaining a smooth and uniform surface, or even scratches the workpiece. Therefore integer speed ratio should be avoided when selecting process parameters.

3) It shows sparser trajectory and becomes more sparser with speed ratio \( r \) increases (shown in Fig. 3(a), Fig. 3(b), Fig. 4(c), Fig. 4(d)) when speed ratio is multiple of 0.2 relative to other values no matter in certain eccentricity polishing or Linear interpolation swing uncertain eccentric polishing, which shows that is beneficial to obtain smooth and uniform surface. Therefore taking speed ratio \( r \) to be multiple of 0.2 and greater into prior consideration when selecting process parameters.

4) Compared to certain eccentricity polishing, it shows more complex trajectory (comparing Fig. 4(a) and Fig. 3(a), Fig. 4(b) and Fig. 3(d)) in linear interpolation swing uncertain eccentric polishing under the identical condition, which shows that is beneficial to obtain smooth and uniform surface in linear interpolation swing uncertain eccentric polishing.

3.2. The effect of eccentricity \( e \) on abrasive particle trajectory

Eccentricity range is generally larger than the radius of the workpiece (\( e \geq r_w \)) no matter in certain eccentricity polishing or linear interpolation swing uncertain eccentric polishing. When the eccentricity is equal to the radius of the workpiece, abrasive trajectory becomes the most intensive with the eccentricity \( e \) increases, the trajectory goes through the workpiece gets smaller and smaller (shown in Fig. 3(e), Fig. 3(f), Fig. 4(e), Fig. 4(f)). Therefore selecting a smaller eccentricity \( e \) is beneficial to improve surface quality in MR effect-based ultra-precision plane polishing.

3.3. The effect of abrasive particle location \( r_p \) on abrasive particle trajectory

Location \( r_p \) of abrasive represents the distance from particle \( P \) to the center \( O \) of polish disk, whose range is \( e - r_w \leq r_p \leq e + r_w \). When eccentricity \( e \) is constant, simulation (shown in Fig. 3(g), Fig. 3(h), Fig. 4(g), Fig. 4(h)) is conducted by selecting different \( r_p \). It can be figured out that the greater the \( r_p \), the less the trajectory through workpiece, which explains the phenomenon of ununiform surface in certain eccentricity polishing or linear interpolation swing uncertain eccentric polishing.

3.4. The effect of swing frequency \( F \) on abrasive particle trajectory

Swing frequency \( F \) represents the relationship between swing speed \( V \) and swing scope \( A \) comprehensively, which is more representative than single factor \( V \) or \( A \). According to the simulation by selecting different \( F \), the sparse trajectory (shown in Fig. 4(e), Fig. 4(f)) generates when value \( F \) is multiple of 0.2, which is consistent with trajectory of certain eccentric polishing, while very dense trajectory (shown in Fig. 4(c), Fig. 4(d), Fig. 4(g), Fig. 4(h)) generates while \( F \) is odd times of 0.01. It explains that reasonable value \( F \) should be selected rather than increasing swing scope \( A \) or swing speed \( V \) simply in linear interpolation swing uncertain eccentric polishing.

4. Experimental research

4.1. Experimental device
Flat polishing device based on cluster MR effect is designed based on principle of cluster MR effect and characteristic of the process, also the servo motion, programming control of CNC milling machine to achieve the motion control of polishing process. As is shown in Fig. 5 that different speed ratio \( r \) can be obtained with polish disk rotation \( (C1) \) and rotation \( (C2) \) of CNC milling machine spindle coils to its z axis, and simulation control of certain eccentric polishing and kinds of uncertain eccentric polishing can be obtained with linear translation of worktable in axis X and Y.

4.2. Optimization of process parameters and experimental results

Optimized process parameters of MR effect-based ultra-precision plate polishing can be obtained according to simulation results. We mainly optimized the process parameters in uncertain eccentricity polishing of X direction because trajectory of abrasive particle in uncertain eccentricity polishing is superior to that in certain eccentricity polishing. MR effect-based chain string on the abrasives makes them in a semi-fixation state to form uniform polishing pad on the polishing disk under MR effect during the ultra-precision polishing based on cluster MR effect, so rotation speed of workpiece is advisable be too large, a group of optimized parameters from simulation: \( r = 4.8 \) \( (\omega_1 = 60 \text{rpm}, \omega_2 = 288 \text{rpm}) \), \( e = 60 \text{mm} \), \( F = 2.61 \) \( (A = 10 \text{mm}, v = 16.1 \text{mm/s}) \).

Polishing experiments are carried out on single crystal SiC for 30min by using the above parameters, three-dimensional morphology and roughness of 6H-SiC are observed under AFM of DI/MultiMode from Veeco Company from America. As is shown in Fig. 6, the polished surface is smooth and uniform, also the roughness Ra decreases by an order of magnitude from 72.89nm to 1.9nm after polishing for 30min. It is concluded that parameters optimization by trajectory simulating in ultra-precision plate
polishing based on cluster MR effect for single crystal SiC substrate not only can obtain an ultra-smooth surface but also high efficiency, which verified the correctness of the simulation analysis.

5. Conclusions

In this study, kinematic model of abrasive particles for certain eccentric and linear interpolation swing uncertain eccentric, uncertain eccentricity of X direction and Y direction in plane polishing based on cluster MR effect are built and simulation analysis is conducted, the following conclusions are drawn out from the results:

1. The key factors such as rotation speed ratio \( r \), eccentricity \( e \), the distance \( r_p \) from particle P to the center \( O \) of polish disk and swing frequency \( F \) have a significant influence on polishing quality.

2. The polishing quality in uncertain eccentricity polishing is superior to that in certain eccentricity polishing but speed ratio should not be multiple of 0.2, otherwise the machined result is not significant. Particularly intense trajectory shows when 2nd place of decimals of value \( F \) is multiple of 0.02, which is beneficial to improve surface quality of workpiece.

3. The polishing quality is better when speeds of workpiece and polish disk are in contrary, it shows sparser trajectory and becomes sparser with speed ratio \( r \) increases when speed ratio \( r \) is multiple of 0.2.

4. The greater the eccentricity \( e \), the less the trajectory through the workpiece, the greater the \( r_p \), the less the trajectory through the workpiece, which explain the phenomenon of ununiform surface in certain eccentricity polishing or linear interpolation swing uncertain eccentric polishing.

5. Polishing experiments are carried out on self designed plate polishing device based on cluster MR effect of single crystal SiC for 30min by using optimized parameters, the roughness \( Ra \) decreases by an order of magnitude from 72.89nm to 1.9nm, which verified feasibility of the cluster MR effect-based ultra-precision plate polishing for single crystal SiC and correctness of the simulation analysis.

Acknowledgements

The authors gratefully acknowledge the financial support from the NSFC- Foundation of Guangdong Province, China (U1034006) and the Key Project of the Natural Science Foundation of Guangdong Province, China (No. 9251009001000009).

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