A Novel Eccentric Lapping Method with Two Rotatable Lapping Plates for Finishing Cemented Carbide Balls

C. C. Lv, Y. L. Sun, D. W. Zuo

Abstract—Cemented carbide balls are usually implemented in industry under the environment of high speed, high temperature, corrosiveness and strong collisions. However, its application is limited due to high fabrication cost, processing efficiency and quality. A novel eccentric lapping method with two rotatable lapping plates was proposed in this paper. A mathematical model was constructed to analyze the influence of each design parameter on this lapping method. To validate this new lapping method, an orthogonal experiment was conducted with cemented carbide balls (YG6). The simulation model was verified and the optimal lapping parameters were derived. The results show that the surface roundness of the balls reaches to 0.65um from 2um in 1 hour using this lapping method. So, using this novel lapping method, it can effectively improve the machining precision and efficiency of cemented carbide balls.

Keywords—Cemented carbide balls, eccentric lapping, high precision, lapping tracks, V-groove.

I. INTRODUCTION

PRECISION ball, as the basic component of high precision machine, is mainly used in high precision bearings, gyroscopes, roundness-measuring instruments, ball valves, and other precision components. As the precision machining equipment requires high speed, high precision and high reliability, the critical ball also has a higher request in terms of geometry, surface quality, and consistency. The steel balls and ceramic balls are widely used at present. However cemented carbide balls outperform in, high hardness, high density, abrasion resistance, corrosion resistance, and the suitability of harsh environment, which leads to an increasing demand, especially in the application of aerospace and oil exploitation. Cemented carbide ball production process can be divided into three steps: cemented carbide powder sintering, casting and machining. Machining stage is the most difficult and also the most important step among the three, which decides the size, shape and surface quality of the cemented carbide ball. However, little study has been done on high-precision

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cemented carbide balls. The size, shape precision and surface quality of the cemented carbide ball have not been effectively improved, which prevents their widespread applications.

In industry, cemented carbide balls are generally finished by traditional V-groove lapping. As shown in Fig. 1 (a), two plates are placed face to face, while the lower plate is machined concentric circular V-groove for placing balls. This process only involves motions on two directions, loading pressure from the top plate and rotating the lower lapping plate. Because of the simple structure, straightforward control and much simpler equipment, this method is widely used in production nowadays. A lot of researches had been done on this method [1]-[3]. However, the precision of balls processed by this method is not sound enough, and the simulation of this method also shows that the lapping tracks in this method are only three concentric circles [4], as shown in Fig. 1 (b). As we all know, the tracks are very important for lapping method. Only the lapping tracks are homogeneous, will the lapping result be good. Three concentric circles are not enough to cover the ball's surface which means there is no possibility to get high-precision balls. Obviously, other lapping methods for cemented carbide balls are needed.
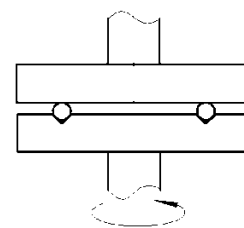

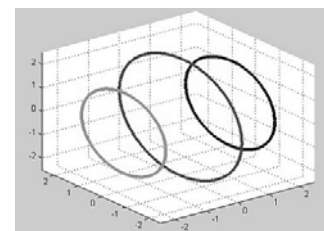Fig. 1 (a) Traditional V-groove lapping method

Fig. 1 (b) Traditional V-groove lapping tricks

Fig. 1 Traditional V-groove lapping method

Here exist a lot of ball-machining methods aiming for other materials, which are inspiring for the research of cemented carbide balls in this study. Angele [5] studied on four shafts ball-lapping and achieved very good results, but the efficiency of this method was too low to be applied in reality. Kurobe et al. [6], [7] modified the traditional V-groove lapping by separating

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the two sides of the V-groove into two parts, and each part can rotate independently. Tani and Kawata [8] developed magnetic fluid grinding which could greatly improve the efficiency of processing. Wang et al. [9] studied on conic grinding and improved sufficiency was found. Wen et al. [10] proposed planetary lapping to manufacture cemented carbide balls. Since all these lapping methods are still in the stage of laboratory research and only the traditional V-groove lapping is applied in real manufacture, it is more practical to study on potential improvements in traditional V-groove lapping thoroughly. Kang and Hadfield [11]-[13] had already done a lot researches on the eccentric V-groove lapping and the precision of balls had been greatly improved. This paper proposes a new lapping method based on the eccentric V-groove lapping where both of the lapping plates, up and down, can rotate separately.

II. KINEMATIC ANALYSIS OF THE NEW METHOD

The most critical requirement of sphere-shaping is that the cutting tracks can evenly cover the entire ball, i.e. the uniformity of the lapping tracks should be guaranteed. In order to make the tracks homogeneous, there are two factors that must be considered, rotation and ball spin angle [14]. During the grinding, only if the ball spin angle is shifting while the ball is rotating, lapping tracks can cover the ball surface, so as to achieve the uniformity.
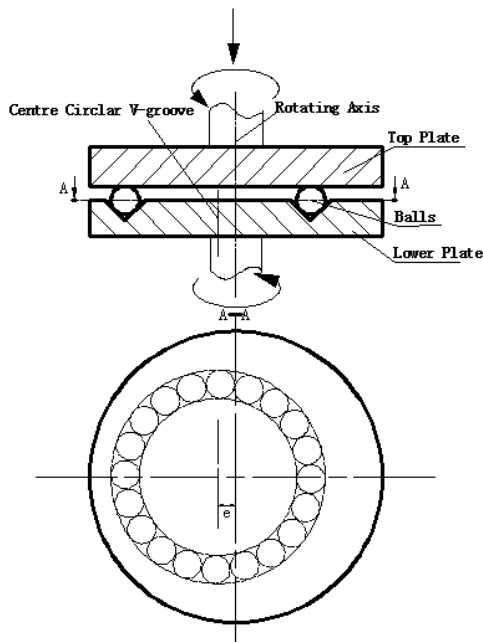

Fig. 2 Schematic of eccentric lapping method with two rotatable lapping plates

Fig. 2 is a schematic illustration of two-rotation-plates eccentric lapping. The top plate is equipped with a flat lapping surface and load pressure and the lower plate with an eccentric V-groove, both can rotate. Because of the eccentricity, it is possible for the ball to change ball spin angle while rotating. With the different speeds of the lapping plates, the ball's spin angle changes in different angle range. Compared to the former

eccentric V-groove lapping, changing the spin angle is more efficient by the rotating of top plate.

In the process of lapping, the plates are in contact with the ball at three points through which the plates drive the ball's rotation and revolution. Fig. 3 shows the contact points between a ball and the plates. The radius from the contact points, A, B, C to the centre of the circular V-groove, R_A, R_B, R_C, and the radius of ball, r, follows (1).
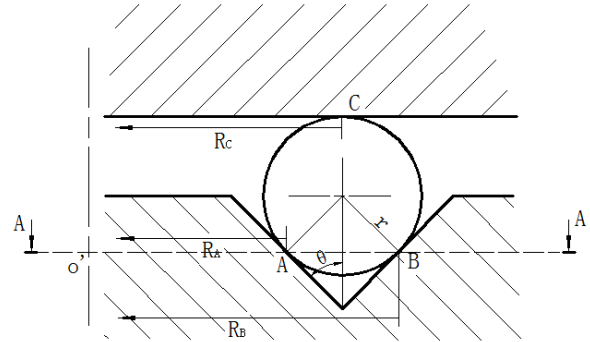

Fig. 3 Three contact points in the two-rotation-plate eccentric lapping method

$$\begin{cases} R_A = R_C - r\cos q \\ R_B = R_C + r\cos q \end{cases} \quad (1)$$

Fig. 4 gives the section A-A in Fig. 3. Point C' is the projected point of point C on the section A-A. The radius from point C' to the centre of the circular V-groove, $R_{C'}$, is equal to R_C. A set of variables are defined, i.e., the lower lapping speed, Ω, the top lapping speed, ω, the radius from the points, A, B, C' to the rotating axis of the lower lapping plate, r_A, r_B, $r_{C'}$, and the angles between OA and O'A, OB and O'B, OC and O'C, AO' and OO', α, γ, β, Φ.
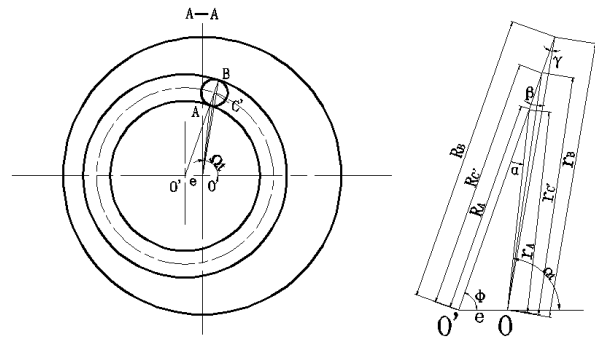

Fig. 4 Geometric analysis of the three points, A, B, C'

If it is assumed that, at time t=0, Φ=0. In triangle AO'O, r_A, R_A, e, Ω, and α follows (2), according to the cosine rule and sine rule.

$$\begin{cases} R_A^2 = e^2 + r_A^2 - 2er_A\cos(p - \Omega t) \\ \dfrac{r_A}{\sin f} = \dfrac{R_A}{\sin(p - \Omega t)} = \dfrac{e}{\sin a} \end{cases} \quad (2)$$

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Equation (2) can be solved as (eliminate negative number)

$$\begin{cases} r_A = \sqrt{R_A^2 - e^2 + e^2 \cos^2(\Omega t)} - e\cos(\Omega t) \\ \alpha = \arcsin(\dfrac{e\sin(\Omega t)}{R_A}) \\ \phi = \arcsin(\dfrac{r_A \sin(\Omega t)}{R_A}) \end{cases} \qquad (3)$$

It is the same in triangle AO'O and triangle C'O'O, and r_B, $r_{C'}$, γ, and β can be derived as

$$\begin{cases} r_B = \sqrt{R_B^2 + e^2 - 2eR_B \cos\Phi} \\ r_{C'} = \sqrt{R_{C'}^2 + e^2 - 2eR_{C'} \cos\Phi} \\ \beta = \arcsin(\dfrac{e\sin\Phi}{R_{C'}}) \\ \gamma = \arcsin(\dfrac{e\sin\Phi}{R_B}) \end{cases} \qquad (4)$$

For the simulation analysis, the following assumptions are made, 1) definite ball diameter, 2) no elastic-plastic deformation, 3) same speed of the lapping plates at the contact points and that of the ball in the circular motion, 4) no mutual friction or collision among balls, 5) lapping fluid effect neglected.

Fig. 5 depicts the relationship of velocities. In Fig. 5 (a), the lower plate linear speed at point A, B, C' perpendicular to the radial plane through the centre of the lower plate, V_{AO}, V_{BO}, $V_{C'O}$, are respectively given by

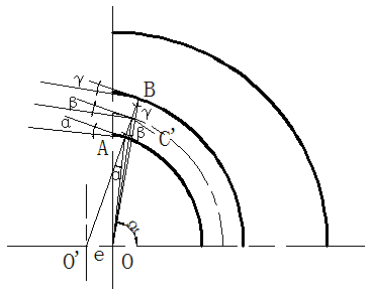$$V_{AO} = \Omega r_A, \quad V_{BO} = \Omega r_B, \quad V_{C'O} = w r_{C'} \qquad (5)$$

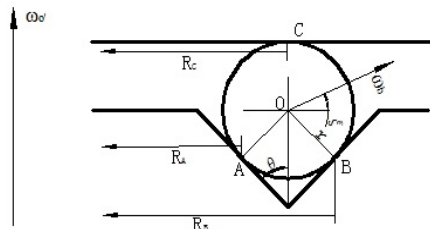Fig. 5 (a) Linear velocities at point A, B, C'

Fig. 5 (b) Definition for ball kinematics variables

Fig. 5 Relationship of velocity

The lower plate linear speed at the point A, B, C' perpendicular to the radial plane through the centre of the

circular V-groove, V_A, V_B, $V_{C'}$ is given by

$$\begin{cases} V_A = V_{AO}\cos\alpha = \Omega r_A \cos\alpha \\ V_B = V_{BO}\cos\gamma = \Omega r_B \cos\gamma \\ V_{C'} = V_{C'O}\cos\beta = \omega r_{C'} \cos\beta \end{cases} \qquad (6)$$

In Fig. 5 (b), variables related to ball kinematics are defined, i.e., ball spin angular speed, ω_b, ball spin angle ξ, and ball circulation angular speed $\omega_{O'}$. Therefore the lower plate linear velocity, V_A, V_B, $V_{C'}$ can also be derived as

$$\begin{cases} V_A = R_C \omega_{O'} + r\omega_b \sin(\xi - \chi) \\ V_B = R_C \omega_{O'} + r\omega_b \cos(\xi - \chi) \\ V_C = R_C \omega_{O'} + r\omega_b \cos\chi \end{cases} \qquad (7)$$

By combining (6) and (7), the variables, ω_b, $\omega_{O'}$, ξ are obtained by

$$\begin{cases} \chi = \arctan(\dfrac{\sin q - \cos q - k - k\sin q}{\cos q + \sin q - k\cos q}) \\ \omega_b = \dfrac{r_A \Omega \cos\alpha - r_B \Omega \cos\gamma}{r[\sin(\xi - \chi) - \cos(\xi - \chi)]} \\ \omega_{O'} = \dfrac{r_C \omega \cos\beta + r\omega_b \cos\chi}{R_C} \end{cases} \qquad (8)$$

with k,

$$k = \dfrac{r_A \Omega \cos\alpha - r_B \Omega \cos\gamma}{r_A \Omega \cos\alpha - r_C \omega \cos\beta} \qquad (9)$$

According to (8), three important variables, ω_b, $\omega_{O'}$, ξ, are derived. These variables directly determine the lapping tracks. It is concluded that the lapping tracks are not only related to eccentricity, e, V-groove half-angle, θ, lower lapping speed, Ω, radius from the centre of the circular V-groove to point C, R_C, ball radius, r, but also related to the top lapping plate angular speed, ω. Therefore it is feasible to control the ball spin angle by manipulating the top lapping speed, ω, which is different from the former eccentric lapping with one rotatable lapping plate.

III. SIMULATION AND DISCUSSION

The V-groove half-angle, θ, has little effect on the precision of balls [12] and the most common value of the half-angle is 45 degree. Whereas the influence of the eccentricity, e, lower lapping speed, Ω, radius of V-groove, R_C, top lapping speed, ω, is not clear in the eccentric lapping method with two rotatable lapping plates. In order further understand the impact of these parameters on the precision of balls, simulation of this lapping method is carried out. In this section, a simulation model is established based on MATLAB 2012.

As the radius of balls is definite, the ball kinematics variables, ω_b, $\omega_{O'}$, ξ, are enough for confirming the lapping tracks. The lapping tracks are three continuous curves, and it is convenient to do discrete sampling with a certain time interval,

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Δt, in the simulation. After calculating the contact point coordinates and outputting them in the 3D coordinates, the lapping tracks are presented.

As shown in Fig. 5 (b), the center of the ball is set as origin for the coordinate, and the coordinates of the three contact points at initial time are represented as

$$\begin{cases} P_C = (0 \quad 0 \quad r)^T \\ P_A = (-r\cos q \quad 0 \quad -r\sin q)^T \\ P_B = (r\cos q \quad 0 \quad -r\sin q)^T \end{cases} \quad (10)$$

and the components of the vector of axis f on the XYZ coordinate axis, L_1, L_2, L_3, are

$$\frac{\bar{L}}{|\bar{L}|} = (L_1, L_2, L_3)^T. \quad (14)$$

In this paper, the three contact points are always in the same plane through the centre of the circular V-groove, so L_1, L_2, L_3, are given by

$$L_1 = \cos q, \qquad L_2 = \sin q, \qquad L_3 = 0. \quad (15)$$

Such that, the coordinates of the point i is described as

$$P_i = Rot(\psi_i)P_{i-1} \qquad i = 1, 2, 3.... \quad (16)$$

The rotation angle of the ball in the sampling time, ψ_i, is derived as

$$\psi_i = \frac{w_{b(i)} + w_{b(i+1)}}{2}\Delta t \quad (17)$$

and the spin angular speeds of point i and point (i+1), $\omega_{b(i)}$, $\omega_{b(i+1)}$, can be obtained by (6).

Following (10)-(17), it is able to get the coordinates of the three contact points at any sampling time. Similarly the trajectory within a certain time period is also attainable. If the uniformity of these coordinates is studied, it is credible to make a prediction for the precision of balls. Fig. 6 shows the lapping tracks of 500 times rotation of the lower plate which is achieved with the lapping conditions as: R_C=35mm, r=6.35mm, Ω=120rpm, ω=50rpm, e=12mm, θ=45°, Δt=0.0001s. When compared it with situation in Fig. 1 (b), the result shows that the efficacy of eccentric lapping method with two lapping plates is much better than that from the conventional V-groove lapping.

To further study the uniformity of the lapping tracks, the spherical surface should be divided in accordance with its latitude and longitude. In this paper, the surface is divided into 100 sections, as shown in Fig. 7.
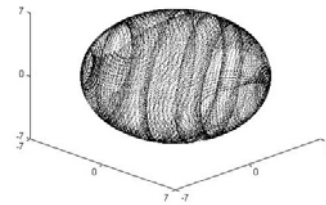
with,

$$P_0 = (P_A \quad P_B \quad P_C) \quad (11)$$

After revolving around an axis f (the spin axis), point P_0 change into point P_1. According to the Euler-angles rotation formula [15], the coordinates of the point, P_1, is derived as

$$P_1 = Rot(\psi)P_0 \quad (12)$$

with Euler-angles rotation matrix as:

$$Rot(\psi) = \begin{bmatrix} L_1^2(1-\cos\psi)+\cos\psi & L_1L_2(1-\cos\psi)-L_3\sin\psi & L_1L_3(1-\cos\psi)+L_2\sin\psi \\ L_1L_2(1-\cos\psi)+L_3\sin\psi & L_2^2(1-\cos\psi)+\cos\psi & L_2L_3(1-\cos\psi)-L_1\sin\psi \\ L_1L_3(1-\cos\psi)-L_2\sin\psi & L_2L_3(1-\cos\psi)+L_1\sin\psi & L_3^2(1-\cos\psi)+\cos\psi \end{bmatrix} \quad (13)$$

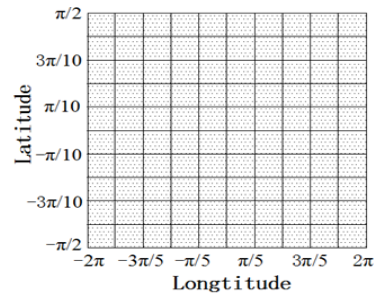Fig. 6 Simulation of the lapping tracks

Fig. 7 Division method of the spherical surface

The area of each section, S_i, can be obtained by (18) and the number of coordinates in each section, Q_i, can be calculated by MATLAB. Take N_i as the ratio of Q_i-to-S_i. The standard deviation of N_i, SD_N, indicating the uniformity of the lapping tracks, can be derived by (19). The smaller SD_N is, the better the uniformity will be, and so will be the precision of balls, vice versa.

$$S = \oint \oint ds = \int_{e_1^i}^{e_1^{i+1}} \int_{e_2^j}^{e_2^{j+1}} r^2 \cos e_2 \, de_1 \, de_2 = \frac{p}{5}r^2 \left| \sin e_2^{j+1} - \sin e_2^j \right| \quad (18)$$

and, ε_1 is the longitude while ε_2 is the latitude.

$$SD_N = \left(\sum (N_i - \bar{N})^2 / n - 1 \right)^{1/2} \quad (19)$$

$\bar{N}$ is the average of N_i.

To take standard deviation of N_i, SD_N, as index, the parameters, eccentricity, e, lower lapping speed, Ω, radius from the centre of the circular V-groove to point C, R_C, top lapping speed, ω, are observed by orthogonal test. A standard

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orthogonal table is used as it can operate four parameters, each at three levels. The parameters and their levels are shown in Table I.

TABLE I
PARAMETERS AND THEIR LEVELS

Level	Parameters			
	A: Eccentricity(mm)	B: Radius of V-groove-circle (mm)	C: Lower lapping speed (rpm)	D: Top lapping speed (rpm)
1	4	35	60	0
2	8	55	90	25
3	12	75	120	50

TABLE II
SIMULATION RESULTS

Parameters No.	A: Eccentricity (mm)	B: Radius of V-groove-circle (mm)	C: Lower lapping speed (rpm)	D: Top lapping speed(rpm)	SD_N
1	4	35	60	0	27.8
2	4	55	90	25	25.7
3	4	75	120	50	26.7
4	8	35	90	50	20.2
5	8	55	120	0	22.8
6	8	75	60	25	24.2
7	12	35	120	25	7.4
8	12	55	60	50	8.4
9	12	75	90	0	29
K_1	80.20	55.40	60.40	79.60	
K_2	67.20	56.90	74.90	57.30	
K_3	44.80	79.90	56.90	55.30	
k_1	26.73	18.47	20.13	26.53	
k_2	22.40	18.97	24.97	19.10	
k_3	14.93	26.63	18.97	18.43	
R	11.80	8.16	6.00	8.10	

This simulation is under the lapping conditions r=6.35mm, Δt=0.0001s, and 100 times rotation of the lower plate. The results are shown in Table II.

According to the range analysis, eccentricity has the most significant impact on the lapping tracks, followed by the radius of V-groove-circle. The third one is the top lapping speed whereas the effect of the lower lapping speed has the minimal influence. Fig. 8 shows the result from the level average analysis by SD_N.

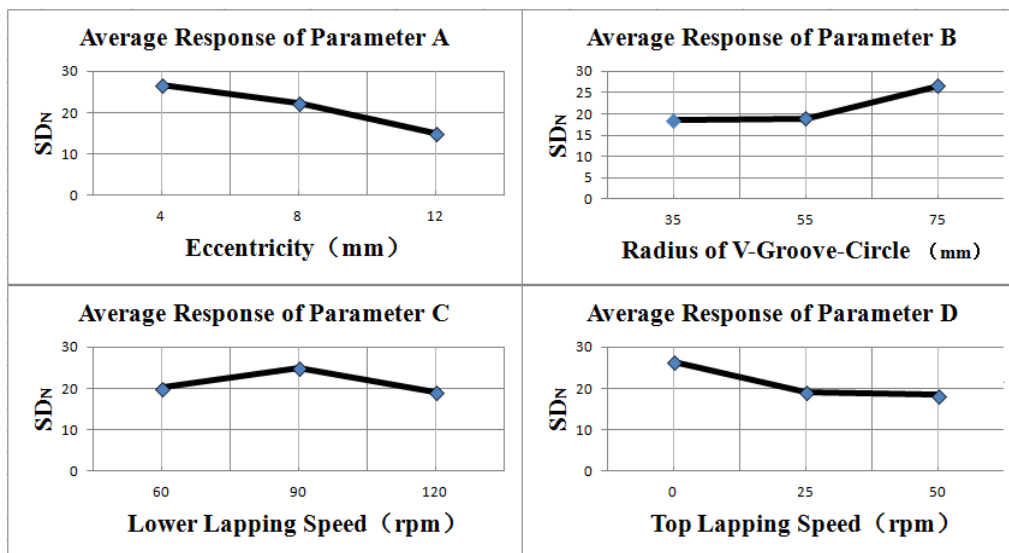Fig. 8 The effect of parameters on SD_N

For eccentricity, the average SD_N is reduced from 26.73 to 22.40 as the eccentricity value increases from 4mm to 8mm. The decrease of the average SD_N is 4.33 and it indicates more homogeneous lapping tracks and higher precision. As the eccentricity value increases from 8mm to 12mm, the average SD_N decreases from 22.40 to 14.93, i.e. a decrease of 7.47 and it

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indicates that the lapping tracks get more homogeneous. However, it is known that the eccentricity has an impact on the distribution of force. The distribution of force will get more uneven as the eccentricity increases which will eventually reduce the accuracy of balls. So the value of eccentricity should not be excessive in real production. For the three eccentricity value, in the simulation, the relatively optimal value is 12mm.

For radius of V-groove-circle, the average SD_N increases from 18.47 to 18.97 as the radius increases from 35mm to 55mm. The increase of the average SD_N is 0.5. From 55mm to 75mm, although the radius increases by the same amount, the average SD_N soar to 26.63. Therefore the radius has a great influence on the precision of balls while it gets bigger and it is better to get the radius small. However, if the radius becomes too small, little balls will be produced in the V-groove and the productivity will be low. The same as the eccentricity, the radius can make an effect on the distribution of force. The distribution of force will become more uneven with the increase of the radius. Therefore the radius should be chosen based on the requirements of precision and productivity. As to the three radius value, in the simulation, the optimal value is 35mm.

For lower lapping speed, average SD_N increases from 20.13 to 24.97 as the speed increases from 60rpm to 90rpm. The increment of the average SD_N is 4.84, which demonstrates more heterogeneous lapping tracks and worse precision. However, from 90rpm to 120rpm, the speed value increases by 30rpm whereas the average SD_N decreases by 6 and the precision will also be improved. There should be a threshold for the lower lapping speed, below which the precision will be better as the lower lapping speed increases, vice versa. In this simulation, the optimal value is 120rpm.

For top lapping speed, the average SD_N reduces from 26.53 to 19.10 as the speed value increases from 0 rpm to 25rpm. And the average SD_N continue to decreases from 19.10 to 18.43 as the speed value increases by 25 rpm. With reference to this declined slope, there may be an optimum value for the top lapping speed. So far it was found in the simulation that the optimal value is 50 rpm.

To sum up, a better level of precision should be conduct in accordance with following lapping conditions: R_C=35mm, r=6.35mm, Ω=120rpm, ω=50rpm, e=12mm.

IV. Experiments and Discussion

During the lapping process, there exist many factors affecting the precision of balls, including load pressure, abrasive, lapping speed, plate material, equipment error, etc. In this paper, eccentricity, radius of V-groove-circle, lower lapping speed, and top lapping speed are discussed and other lapping conditions are listed in Table III. An orthogonal experiment is conducted by the authors to verify the feasibility of this lapping method. An isolated ring is used in this experiment to prevent collisions between balls.

TABLE III
LAPPING CONDITIONS

Ball being lapped	Φ12.701mm,YG6 ball blanks Roundness:2um
Lapping machine	SPQMJ-350 Lapping machine based on eccentric lapping method with two rotatable lapping plates
Lapping plates	Nodular cast iron
Abrasive material	W1.5, Silicon Carbide
Base fluid	Deionizer water
Abrasive concentration	10wt%
Time	1h/batch
Amount of lapping ball	3 ball/batch
Load pressure	20N/ball

The parameters in this experiment are identical with that in the simulation, as listed in Table I. Roundness of the balls is employed as index for quantitative evaluation. The results are shown in Table IV.

TABLE IV
EXPERIMENT RESULTS

NO.	Parameters				Index
	A: Eccentricity(mm)	B: Radius of V-groove-circle(mm)	C: Lower lapping speed(rpm)	D: Top lapping speed(rpm)	Roundness(μm)
1	4	35	60	0	1.25
2	4	55	90	25	1.22
3	4	75	120	50	1.08
4	8	35	90	50	1.08
5	8	55	120	0	0.92
6	8	75	60	25	1.18
7	12	35	120	25	0.78
8	12	55	60	50	0.65
9	12	75	90	0	1.20
K1	3.550	3.117	3.083	3.367	
K2	3.183	2.783	3.500	3.183	
K3	2.633	3.467	2.783	2.817	
k1	1.183	1.039	1.028	1.122	
k2	1.061	0.928	1.167	1.061	
k3	0.878	1.156	0.928	0.939	
R	0.306	0.228	0.239	0.183	

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The contributions to the efficiency from this lapping method are shown in Fig. 9. The experiment results show that the most significant impact on the lapping tracks relies on the eccentricity, followed in order by lower lapping speed and the radius of V-groove-circle whereas the effect of the top lapping speed is minimal. The results in the experiment differ from the outcomes from the simulation. In the experiment, the influence of eccentricity and top lapping speed is smaller than that in the simulation, the influence of radius of V-groove-circle remains unchanged, whereas the influence of the lower lapping speed gets more substantial. Sliding is ignored in the simulation, but it actually exists in lapping process. Sliding is one of the main causes of vibration of lapping tracks and it contributes to the difference between simulation results and experiment results. Although it is difficult to confirm the specific effects of sliding, the influence of top lapping speed is verified in both simulation and experiment.
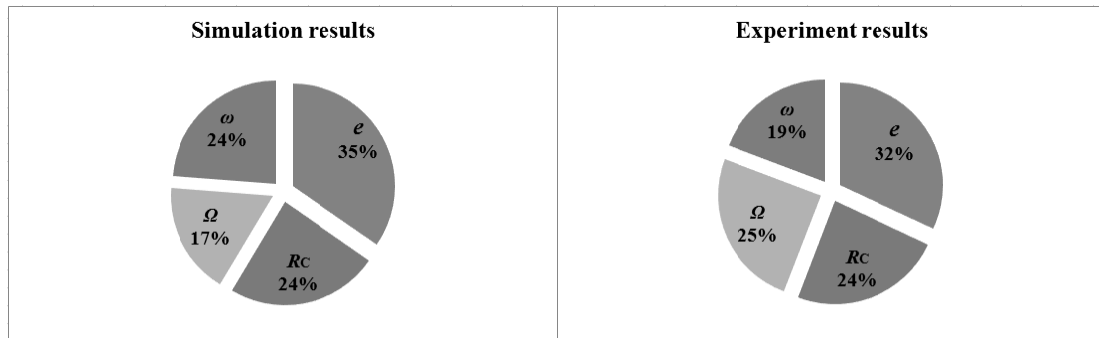

Fig. 9 Percentage contributions for parameters e, R_C, Ω, and ω

Fig. 10 shows the result from the level average analysis by roundness. According to the experiment results, the best precision could be obtained under the following lapping conditions: R_C=55mm, r=6.35mm, Ω=120rpm, ω=50rpm, e=12mm. The influence of eccentricity, lower lapping speed, and top lapping speed are similar to which in the simulation and the results manifest the simulation. The only difference is in the effect of radius of V-groove-circle. The optimal value of radius of V-groove-circle is 55mm in the experiment whereas it is 35mm in the simulation. The difference is deemed to be caused by the uneven force.
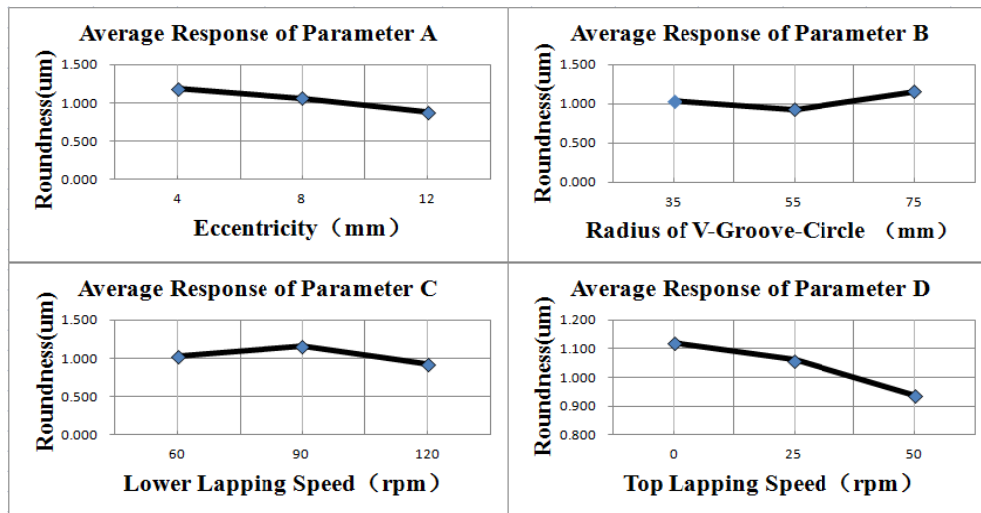

Fig. 10 The effect of parameters on roundness

The distribution of force is related with the radius from the ball-top lapping plate contact point to the rotating axis of the lower lapping plate, r_c. As shown in Fig. 11, the bigger the value of r_c is, the smaller the force is. And the value of r_c can be obtained by (4), which indicates that both eccentricity and radius of V-groove-circle make effect on r_c. Therefore, if the value of eccentricity and radius of V-groove-circle vary too significantly, the uneven distribution of force will be exacerbated. Due to the uneven distribution of force, the lapping depth of the balls will not be constant as balls are rolling, such that the precision of balls will be worse. In the experiment, the radius of V-groove-circle shows a bigger impact on the distribution of force than the eccentricity and the value, 35mm, is small enough to reduce accuracy.
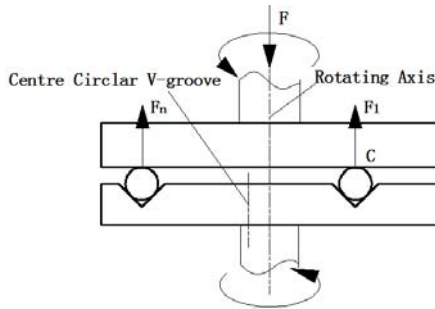
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Fig. 11 Distribution of lapping force

V. CONCLUSION

In this paper, a novel eccentric lapping method with two rotatable lapping plates was proposed. The method was tested with both a simulation program and an orthogonal experiment. Based on the results, the following conclusions can be drawn:

1. It is certain that the lapping tracks obtained by this method are able to cover the surface of balls. A great influence on this lapping method by the top lapping speed is ascertained in both simulation and experiment. The optimum lapping parameter for the roundness within the experiment level: R_C=55mm, r=6.35mm, Ω=120rpm, ω=50rpm, e=12mm.

2. Among all of the design parameters, the influence on the lapping precision by lapping parameters are studied in the experiment, the most significant impact on the lapping tracks relies on the eccentricity (32 percent), followed by the lower lapping speed (25 percent) and radius of V-groove-circle (24 percent), the top lapping speed performs minimal effects (19 percent).

3. With the help of newly-proposed lapping method, the cemented carbide balls (YG6) could reach a roundness of 0.65um from formerly 2um in an hour. The eccentricity lapping method with two rotatable lapping plates was validated as an effective way for processing cemented carbide balls finishing.

Further study will be continued and the influence of the lapping pressure, lapping fluid, abrasive etc. will be involved.

APPENDIX

R_A radius from the centre of the circular V-groove to the ball-V-groove inner contact point (point A)

R_B radius from the centre of the circular V-groove to the ball-V-groove outer contact point (point B)

R_C radius from the centre of the circular V-groove to the ball-top lapping plate contact point (point C)

r ball radius

Θ V-groove half-angle

$R_{C'}$ radius from the centre of the circular V-groove to point C' (the subpoint of point C in the plane parallel to the lapping plate and through the lower two contact points)

r_A radius from the rotating axis of the lower lapping plate to point A

r_B radius from the rotating axis of the lower lapping plate to point B

r_C radius from the rotating axis of the lower lapping plate to point C'

Ω lower lapping speed

ω top lapping speed

e eccentricity (the radius from the rotating axis and the centre of the circular V-groove)

ω_b ball spin angular speed

$\omega_{O'}$ angular speed of ball circulation around the circular V-groove

ξ ball spin angle

V_{AO} lower plate linear speed at point A perpendicular to the radial plane through the centre of the lower plate

V_{BO} lower plate linear speed at point B perpendicular to the radial plane through the centre of the lower plate

$V_{C'O}$ lower plate linear speed at point C' perpendicular to the radial plane through the centre of the lower plate

V_A lower plate linear speed at point A perpendicular to the radial plane through the centre of the circular V-groove

V_B lower plate linear speed at point B perpendicular to the radial plane through the centre of the circular V-groove

$V_{C'}$ lower plate linear speed at point C' perpendicular to the radial plane through the centre of the circular V-groove

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