Effect of the geometry of workpiece on polishing velocity in free annular polishing

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Base on Coulomb friction model, the workpieces with different geometry rotating in free annular polishing are simulated. From simulation, the following conclusions are drawn. The angular velocity of workpiece is higher than that of polishing pad if the ring rotates uncontrolled in free annular polishing. The circular workpiece can synchronize with polishing pad through controlling the rotation of ring, which depends on the radii of ring and workpiece, the friction coefficients of polishing pad-workpiece and ring-workpiece, and the angular velocity of polishing pad. The workpiece with sharp corner cannot contact with the ring contiguously, which causes the contact state changing and the angular velocity of workpiece fluctuating ceaselessly, and this type of workpiece should be controlled with clamp to rotate synchronistically with the polishing pad.

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Chemical mechanical polishing (CMP) is one of the most effective planarization technologies in integrated circuit (IC) industry and optics industry. During the CMP process, two important factors that affect the processing quality and the productivity are pressure and relative velocity, which are expressed by Preston[1] firstly. No matter plane or spherical polishing, the dense and unrepeated traces in workpiece surface are required in order to obtain fine finishing surface. Several researchers have worked on the relative velocity and traces of workpiece and polishing pad. They concentrated on several aspects: 1) only the relative velocity, which is deduced mathematically from the geometry relationship between workpiece and polishing pad[2−5]; 2) the relative velocity and the trajectory of the random point on workpiece moving on polishing pad[6−9]; 3) the relative velocity and the torque deduced from geometry relationship between workpiece and polishing pad with considering the friction between workpiece and polishing pad[1,10−12], even the eccentricity of the workpiece[12,13]. Preston studied the rotational motion of an infinitely narrow driven ring with fixed parallel axes and gave a new solution[1]. Cooke *et al.* described the annular lapping machine and the corresponding theory and practice[2].

However, the geometry of workpiece should be considered, as well as the relative velocity between workpiece and polishing pad in free polishing, because the geometry of workpiece will affect the friction force and relative motion between the polishing pad and workpiece, which is also one of the reasons that the optical polishing needs the experienced and skilled technician to treat different geometries of workpiece in practice. In this paper, we will analyze the geometry difference of workpiece in annular polishing with simulating the change of relative velocity between workpiece and polishing pad by Coulomb friction model.

To simplify the polishing process, we make the following assumptions. 1) The effect of abrasive particles and slurry fluid is ignored; 2) during the polishing process, the workpiece contacts entirely with the polishing pad; 3) the workpiece, polishing pad, and ring are taken as rigid continuum and they have no distortion; 4) the surface of the polishing pad, contacting with the workpiece, is plane; 5) the frictional coefficient of workpiece to polishing pad is constant.

We begin with just considering the workpiece rotating uniformly on polishing pad. Taking a circle centered at O_2 with random radius r on workpiece, as shown in Fig. 1. A line passes through the center O_1 of polishing pad and makes a joint angle θ with O_1O_2, which intersects with circle O_2 at points C and D. The workpiece is subjected to two frictional torques in positive and negative directions simultaneously. The left part of workpiece is subjected to anti-clockwise frictional torque, and the right part to clockwise torque. The point C is in the left side of the workpiece and point D in the right side. The velocity of point C is

$$v_C = (v_{C\mathrm{t}}^2 + v_{C\mathrm{n}}^2)^{1/2}, \tag{1}$$

where the tangent velocity is $v_{C\mathrm{t}} = l_{O_1C}\omega_1 \cos\alpha_C + l_{O_2C}\omega_\mathrm{w}$ and the normal velocity $v_{C\mathrm{n}} = \rho_C\omega_1 \sin\alpha_C$. In a similar way, the velocity of point D is

$$v_D = (v_{D\mathrm{t}}^2 + v_{D\mathrm{n}}^2)^{1/2}, \tag{2}$$

where the tangent velocity $v_{D\mathrm{t}} = l_{O_1D}\omega_1 \cos\alpha_D + l_{O_2D}\omega_\mathrm{w}$ and the normal velocity $v_{D\mathrm{n}} = \rho_D\omega_1 \sin\alpha_D$. l_{O_1C} and

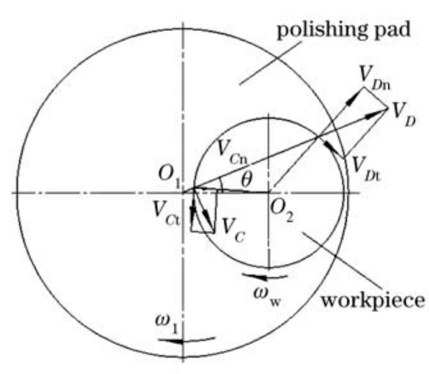

Fig. 1. Velocity analysis of workpiece motion.

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l_{O_1D} are the distances of points C and D to O_1, respectively; α_C and α_D are the acute angles between direction of friction force and velocity direction of the two points C and D, respectively; ω_1 and $\omega_{\rm w}$ are the angle velocities of polishing pad and workpiece, respectively; l_{O_2C} and l_{O_2D} are the distances of points C and D to the center of workpiece. The eccentricity e is the distance between polishing pad center O_1 and workpiece center O_2. From the geometry relationship, we get

$$\cos\alpha_C = \frac{e^2 - l_{O_1C}^2 - r^2}{2l_{O_1C}r}, \tag{3}$$

$$\cos\alpha_D = \frac{e^2 - l_{O_1D}^2 - r^2}{2l_{O_1D}r}. \tag{4}$$

From the above, the velocity and direction are different in all points. Consequently, the friction force which spurs the workpiece rotating on the polishing pad and its direction are different too. The force torques come to balance when the angular velocity of workpiece reaches a given value. Then the rotation of workpiece comes into steady state, and the angular velocity of workpiece becomes uniform.

In a similar way, we can also calculate the angular velocity of ring $\omega_{\rm r}$. When the workpiece rotates, it will contact with the inside surface of the ring, so the different angular velocities of workpiece and ring will change, until they reach the same value. However, the contact states are different for workpieces with different geometries. The contact states are shown in Fig. 2. In Fig. 2(a), the circular workpiece will contact linearly and continuously with the ring when it rotates on polishing pad and within the ring, and the contact point is relatively fixed. In Fig. 2(b), only the corners of the square workpiece contact with the ring when it rotates, and the four corners do not contact with the inside surface of the ring simultaneously, consequently there are only one or two corners at a same time. The unstable contact state makes the contact discontinuity, which causes the angular velocity of workpiece changing with time. The discontinuous contact will cause the workpiece and ring colliding. The non-zero collision causes an instantaneous change in the velocity of workpiece, which will be discussed in the following simulation.

In order to analyze the motions of workpieces with different geometries in free annular polishing, the dynamic analysis software, MSC.ADAMS, is used to simulate the polishing process. In the simulation, the positions of the workpieces placed are shown in Fig. 2. Some parameters used are the same as those in Ref. [10], as listed in Table 1.

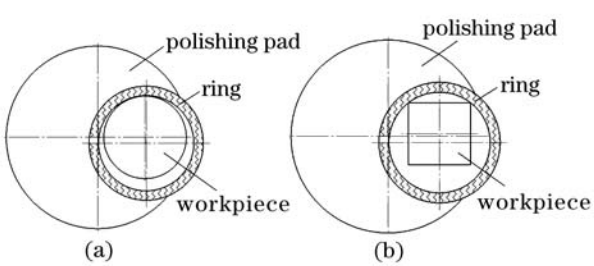

Fig. 2. Contact states of (a) circular and (b) square workpieces.

Table 1. Simulation Parameters in Free Annular Polishing

Parameter	Value
Circular Workpiece Size	$\phi 40 \times 5$ (mm)
Square Workpiece Size	35.445×35.445 (mm)
Annular Velocity of Polishing Pad	16 rpm (1.67552 rad/s)
K8 Glass Elastic Modulus	5950 N/mm^2
K8 Glass Poisson Coefficient	0.211
K8 Glass Density	2.52×10^{-6} kg/mm^3
Pitch Elastic Modulus	2500 N/mm^2
Pitch Poisson Coefficient	0.4
Pitch Glass Density	1.05×10^{-6} kg/mm^3

In the simulation, the material of polishing pad is pitch, and the material of ring and workpiece is K8 glass. So the friction coefficient between the polishing pad and workpiece is different from that between ring and workpiece. The polishing pad connects with ground by revolute joint to ensure that the polishing pad only rotates. The ring connects with ground by cylindrical joint to ensure that the ring not only rotates but also presses on polishing pad by its own dead weight, which causes the friction between polishing pad and ring. The ring contacts with polishing pad by solid-solid contact, and the friction model is Coulomb friction. The workpiece is put on the polishing pad and within the ring, and contacts with them by solid-solid contacts. All friction coefficients are default. Every workpiece state is simulated for three conditions: the first one is the ring rotates freely; the second one is the angular velocity of ring is set at 1.67552 rad/s to equal that of polishing pad; the last one is the angular velocity of ring is set by equation. All simulations are operated for 5 s. The simulation results are shown in Fig. 3.

From Fig. 3(a), we can known that the circular workpiece does not rotate steadily when the angular velocity of polishing pad is 1.67552 rad/s and the ring rotates freely. The angular velocity of circular workpiece is higher than 2.5 rad/s. And the angular velocity of ring is also higher than that of polishing pad. While the uniform removal of workpiece surface comes from the angular velocity synchronization between polishing pad and workpiece[2]. If we set the angular velocity of ring at 1.67552 rad/s, the circular workpiece gets a much higher angular velocity. That is, we should lower the angular velocity of circular workpiece through controlling the angular velocity of ring. From the angular velocity synchronization between polishing pad and workpiece and considering the friction between them, we get

$$\omega_{\rm w} = (1 - \mu_{\rm w})\omega_1, \tag{5}$$

where $\mu_{\rm w}$ is the friction coefficient between polishing pad and workpiece. At the same time, the workpiece contacts with the ring at a point. The linear velocity of workpiece should equal that of the ring at the contact point. Considering the friction, too, we get

$$r_{\rm w}\omega_{\rm w} = (1 - \mu_{\rm r})r_{\rm r}\omega_{\rm r}, \tag{6}$$

where $\mu_{\rm r}$ is the friction coefficient between ring and

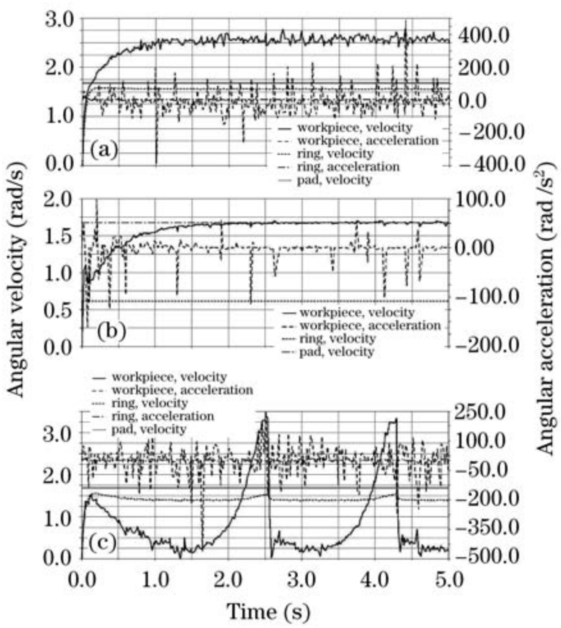

Fig. 3. Simulations of workpieces with different geometries in annular polishing. (a) Circular workpiece, the ring rotates freely; (b) circular workpiece, the ring rotates with angular velocity of 0.60928 rad/s; (c) square workpiece, the ring rotates freely.

workpiece, r_r is the inside radius of ring. We can calculate the angular velocity of ring from Eqs. (5) and (6),

$$\omega_r = \frac{r_w(1-\mu_w)\omega_1}{(1-\mu_r)r_r}. \tag{7}$$

In order to validate the angular velocity of ring, we simulate the circular workpiece in the free annular polishing with the calculated annular velocity of ring (Fig. 3(b)), and in the simulation the materials of ring and workpiece are the same, so their friction coefficients are the same. From Fig. 3(b), the angular velocity of workpiece agrees with that of polishing pad well enough. The angular velocity of workpiece is very smooth compared with that of Fig. 3(a). That is, the annular velocity of ring should be controlled by Eq. (7) to synchronize the angular velocities of polishing pad and workpiece.

For square workpiece, the four corners contact with the inside surface of the ring periodically when the workpiece rotates on the polishing pad and within the ring in free annular polishing simulation (Fig. 3(c)). The alternative contact of four corners of the workpiece causes the angular velocity of workpiece fluctuating between the maximum and minimum values ceaselessly. The angular velocity of ring also changes when the four corners of the workpiece contact with the ring periodically. And the angular velocity of workpiece cannot be controlled through controlling the angular velocity of ring, which needs to be controlled with the clamp.

From the above annular polishing simulation, we can draw the following conclusions. 1) The angular velocity of workpiece is more than that of polishing pad if the ring rotates freely in free annular polishing. 2) The workpiece can synchronize with the polishing pad through controlling the angular velocity of ring by Eq. (7). The angular velocity of ring depends on the radii of ring and workpiece, the friction coefficients of polishing pad-workpiece and ring-workpiece, and the angular velocity of polishing pad. 3) The workpiece with sharp corner cannot contact with the ring contiguously, which causes the contact state changing and the angular velocity of workpiece fluctuating ceaselessly. So this type of workpiece cannot be controlled like circular workpiece. This type of workpiece can synchronize with the polishing pad with a clamp, where the clamp is fixed on the work ring, or floating on the work ring and the angular velocity of workpiece is controlled independently.

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