Material removal model of vertical impinging in fluid jet polishing

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It is important for precise fabrication to research the material removal model of polishing. Simulation is done by computational fluid dynamics for fluid jet polishing (FJP). Numerical research and theoretical description for abrasive particles discrete system are taken by population balance modeling method, and experiments are taken to research the removal profile by vertical fluid jet polishing (VFJP). The results of experiment and simulation show that the removal profile of VFJP turns on a W-shaped profile. By analyzing the material removal mechanism of FJP that material is removed by particles impinging wear and wall movement erosion, the mathematical material removal model of VFJP is enduced. Comparing the mathematical material removal model with the experimental removal profile, it is found that the mathematical material removal model of VFJP is accurate.

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Aspheric optical components can effectively improve the image quality of the optical system, but how to shape and polish the aspheric surfaces has always been a challenge in the optical fabrication industry[1−3]. To overcome the problems, there is a novel polishing method named fluid jet polishing (FJP), which can be used to polish aspheric optics lens with complex surfaces, showing potential application in the optical fabrication industry. The FJP system adopts a nozzle to guide premixed slurry to the workpiece at a high speed, and material is removed by the collision and shearing actions between the abrasive particles and the workpiece[4−6].

In optical manufacturing, material removal function models play an important role in practical computer-controlled optical surfacing. Preston function is usually adopted to describe material removal function[7]. According to Preston's hypothesis, the amount of removed material can be described as a linear function:

$$\frac{\mathrm{d}z}{\mathrm{d}t} = KPV, \tag{1}$$

where z is the material removal ratio, t is time, P is pressure, V is the relative velocity, and K is a constant related to the material properties and other process parameters.

As the complicacy of material removal mode and removal mechanism in FJP, the removal functions for vertical FJP and oblique FJP are different, and the Preston function cannot describe the removal function exactly and completely in FJP. In order to actualize computer-controlled optical surfacing for FJP, it is a problem to establish the material removal model. In this letter, we research the material removal model of vertical FJP. Experiment is taken and material removal result is shown. With further analysis and simulation, the material removal model of vertical fluid jet polishing (VFJP) is established.

The slurry is guided onto a piece of K9 glass with an angle of 90°. A cone-shaped and columned nozzle whose diameter is 1 mm and the premixed slurry with 5% CEROX™1650 grinding compound are chosen. The mean diameter of the abrasive particles is 3 μm, the standoff distance is 10–12 times of the nozzle diameter, and the pressure is 0.8 MPa.

As a result, some material is removed. The exact shape of the spot is shown in the ZYGO interferogram in Fig. 1, and the polishing profile is shown in Fig. 2. We can see that it turns a ring-shaped profile in the polishing region after the material removal, and the profile is a W-shaped. The maximum of material removal is not in the center of the polishing region, while it is the same along

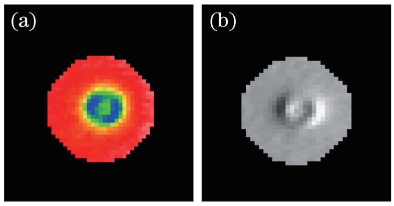

Fig. 1. (a) Phase map and (b) slope X map of the polishing region.

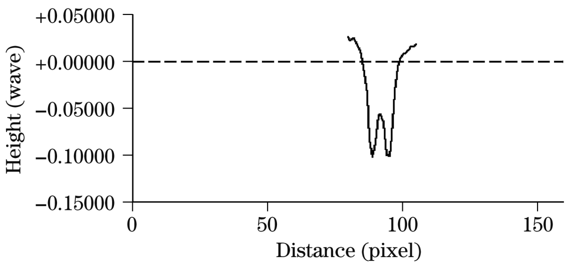

Fig. 2. Profile of the polishing region.

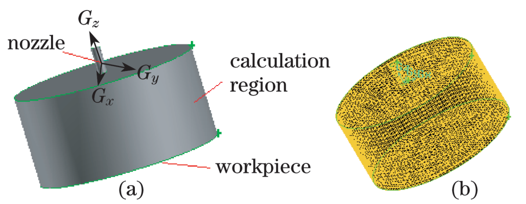

Fig. 3. (a) Physical model and (b) grid model of FJP.

the circumference. The offset in Fig. 1 is induced by the fact that the nozzle cannot be exactly vertical to the surface of workpiece.

The FJP system is a complex multi-phase turbulent flow system, where continual fluid flows with lots of abrasive particles. And between continual phase and discrete phase, there exists some mutual actions which are nonlinear, unsteady, imbalanced, and multi-dimensional. In order to research the material removal model, we have simulated the process of FJP by computational fluid dynamics software, and numerical research and theoretical description for abrasive particles discrete system are taken by population balance modeling method[8,9]. Abrasive particles jet out from the nozzle and impact into the workpiece wall after a free jet process. The physical model is shown in Fig. 3. We have simulated and optimized the standoff distance of nozzle by computational fluid dynamics software, and found that the optimization value of standoff distance was 10–12 times of the nozzle's diameter[10]. So the model takes nozzle's diameter as 1 mm, and standoff distance as 10 mm, the region of workpiece to be calculated is given as a circular region with diameter of 20 mm.

The simulations results are shown in Fig. 4. We can see that the flow crooks to two sides when the fluid jet impinges the workpiece wall. The whole impinging jet can be divided into three regions: free jet region, impingement region, and wall jet region. The variable parameters for abrasive particles, such as wall shear stress, erosion velocity, and wall velocity, are relative and similar, as can be seen from Figs. 4(c)–(f). Wall shear stress is proportional to velocity when particles flow on the workpiece wall, and the erosion of materials is characterized by an erosion rate that increases with velocity and has a maximum at the maximum velocity. The material removal gets the stagnation point when the velocity is zero. The information in Figs. 2 and 4 demonstrates that the material is removed by the erosion and shearing actions between abrasive particles and workpiece. In the wall jet region, the material is removed by the erosion between abrasive particles and workpiece. The material removal function can be described as

$$V = V_{\mathrm{I}} + V_{\mathrm{P}}, \tag{2}$$

where V_{I} denotes the material removed by impinging action in the impingement region, and V_{P} denotes that removed by erosion and shearing actions in the wall jet region.

In the single particle impact action, particle moves with an initial velocity and impacts the target material. The total energy absorbed by the workpiece during impact can be expressed in terms of the plastic deformation energy, stress wave energy, and residual energy. The plastic deformation energy is dissipated in a plastic process, transferring into heat and stored energy in the form of residual strain. The stress wave energy transmits into the body of the target material and is dissipated by fractures and internal friction. The residual energy is the balance of the total input energy. It is partially dissipated by the fragmentation of the particle and the rest becomes the kinetic energy of the rebounding particle or particle fragments. An empirical coefficient f_{e} is supposed to account for the stress wave energy transmitting into the body of the target material, according to Hutchings' model. This energy can be determined as[11]

$$W = \frac{1}{2} m_{\mathrm{p}} u^2 f_{\mathrm{e}} \eta(\nu) \left(\frac{\rho}{\rho_{\mathrm{p}}}\right)^{\frac{1}{2}} \left(\frac{H}{E}\right)^{\frac{3}{2}}, \tag{3}$$

where m_{p} is the mass of particle, $\eta(\nu)$ is Poisson's ratio coefficient, ρ is the density of workpiece, ρ_{p} is the density of particle, u is the velocity of particle impacting the target, E is the elastic modulus, and H is the hardness.

It has been found that the Si–O bond of glass will crack, forming a hydration soft layer when water permeates into the glass surface, and the soft layer is 0.5–12 nm in depth[12]. The material removal occurs in the soft layer in virtue of the low material removal rate in FJP. The material removal model is shown in Fig. 5. The relation between the contact area with target surface by particle and impact depth can be defined as

$$A = \pi[r^2 - (r - h_{\mathrm{I}})^2], \tag{4}$$

where r is the particle radius, and h_{I} is the depth of material removal by a single particle, which is very small compared with r, so A can be simplified as $2\pi r h_{\mathrm{I}}$. The total fracture surface energy is assumed to be a fraction (f_W) of the total stress wave energy (W). Thus, the area removal due to fractures is solved to be $A = \frac{f_W W}{\gamma}$, in which γ is the fracture energy per unit area of target material, described as $\gamma = \frac{K_c^2}{2E}$, where K_c is the fracture

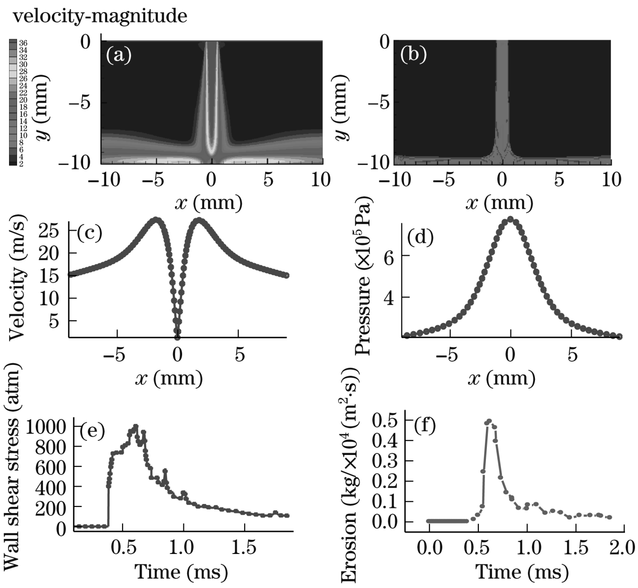

Fig. 4. Simulation results of (a) slurry flow field; (b) particles distribution in flow field; (c) velocity distribution on workpiece; (d) pressure distribution on workpiece; (e) particles wall shear stress; (f) erosion distribution on workpiece.

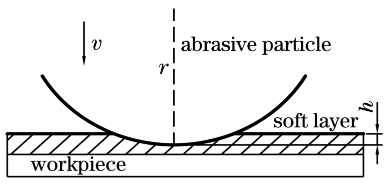

Fig. 5. Impact model of FJP.

toughness. Finally, h_I can be expressed as

$$h_{\rm I} = \frac{f_{\rm e} f_W \eta(\nu) m_{\rm p} u^2}{\pi r} \left(\frac{\rho}{\rho_{\rm p}}\right)^{\frac{1}{2}} H^{\frac{3}{2}} E^{-\frac{1}{2}} K_c^{-2}. \quad (5)$$

In the wall jet region, there is no impinging action to the target but shearing action and erosion. The slurry flows in radial direction, and the slurry velocity gets to fall gradually as it gets the maximum. The material is removed by shearing action and erosion. Based on the erosion study of brittle material by Sheldon[13], we propose a model for single particle erosion in FJP, which supposes that the velocity direction of the particle is parallel to the work piece surface:

$$h_{\rm p} = K \left(\frac{\rho_p}{E}\right)^{\frac{2}{5}} r(u - u_K)^2, \quad (6)$$

where u_K is the critical velocity of the material remove.

The distribution of pressure on the workpiece is a Gauss profile as shown in Fig. 4(d). There is an empirical function to describe the pressure distribution:

$$\frac{P}{P_0} = \exp\left[-0.693\left(\frac{x}{b}\right)^2\right], \quad (7)$$

where P_0 is the maximum pressure at the stagnation place, and b is the value of x when P is equal to $P_0/2$. Then the distribution of stress wave energy can be defined as

$$W(x) = W_0 \exp\left[-0.693\left(\frac{x}{b}\right)^2\right], \quad (8)$$

where W_0 is the maximum pressure at the stagnation place. The distribution of material removal by impinging action can be written as

$$f(x, h_{\rm I}) = \frac{f_{\rm e} f_W \eta(\nu) m_{\rm p} u_0^2 \exp[-0.693(\frac{x}{b})^2]}{\pi r} \times \left(\frac{\rho}{\rho_{\rm p}}\right)^{\frac{1}{2}} H^{\frac{3}{2}} E^{-\frac{1}{2}} K_c^{-2}, \quad (9)$$

where u_0 is the slurry velocity at the orifice of nozzle. Finally, the material removal depth model by single particle is

$$f(x,h) = f(x, h_{\rm I}) + f(x, h_{\rm p}) = \frac{K_1 m_{\rm p} u_0^2 \exp[-0.693(\frac{x}{b})^2]}{r} \left(\frac{\rho}{\rho_{\rm p}}\right)^{\frac{1}{2}} H^{\frac{3}{2}} E^{-\frac{1}{2}} K_c^{-2} + K_2 \left(\frac{\rho}{E}\right)^{\frac{2}{5}} r[u_x(x) - u_K]^2. \quad (10)$$

According to Eq. (10), the unitary removal distribution profile is exhibited in Fig. 6, and the polishing profile is exhibited in Fig. 7. Comparing Fig. 6 with Fig. 7, it is shown that the experimental polishing profile approximately accords with the model profile, and the material removal model is fit for the FJP system.

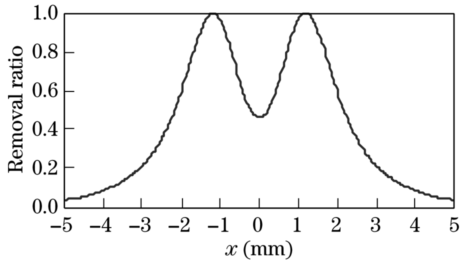

Fig. 6. Material removal model profile.

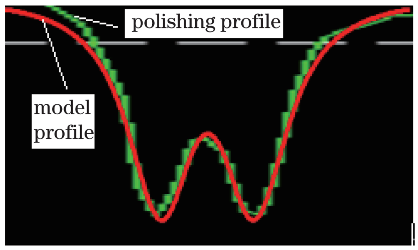

Fig. 7. Comparison between polishing profile and model profile.

In conclusion, by analyzing the material removal mechanism, we establish the theoretical description for material removal spot shape of VFJP, which accords with experimental phenomenon. But the model is not tolerably accurate. It is necessary to take further research on the material removal model, and experiments are needed to get the accurate values of coefficients $f_{\rm e}$, K, and the critical velocity u_K.

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