Analysis of material removal characteristic of hydrodynamic effect polishing with revolution-rotation condition

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Abstract. Hydrodynamic effect polishing (HEP), a non-contact polishing process, can remove the surface/subsurface damage effectively and realize the surface roughness at atomic level. However the HEP process put extremely high demand on the movement accuracy of the polishing equipment. Simulations results show movement errors of the axes will directly affect the polishing effect. There exist tiny polishing marks on the HEP processed surface, and these marks will restrict the improvement of surface quality. The movement and shape errors will cause shear stress and hydrodynamic pressure fluctuation on the workpiece surface, and then the fluctuation are duplicated on the processed surface. The fluctuation can be homogenized with the introduction of revolution movement, and then the tiny polishing marks can be depressed. Material removal characteristic of the HEP with revolution movement has been analyzed. 3D fluid dynamic simulation was conducted under different rotational and revolutionary with different polishing clearance. The analysis will give positive instructions on optimization of the HEP equipment.

1. Introduction
Hydrodynamic effect polishing (HEP), a non-contact ultra-smooth surface processing method, depends on nanoparticle chemical adsorption with the optical workpiece surface in elastic mode to realize material removal. The processing principle is shown in Figure 1[1, 2]. Both the polishing wheel and the workpiece are all immersed in the polishing slurry containing nanoparticles. HEP deepens on high-speed rotation of the polishing wheel to form a lubrication film between the wheel and workpiece to achieve non-contact processing. Nanoparticles enter the film lubrication area under the action of the wheel rotation, and then impact with the workpiece surface forming chemical adsorption at the interface. The impact of the nanoparticles on the workpiece surface is very gentle under the influence of hydrodynamic pressure, and it is easy to control the impact on the workpiece surface in elastic region. There is a large fluid shear stress in the fluid film lubrication zone, and nanoparticles can overcome the bond energy of the surface layer to remove the surface atoms [3-5], and atomic material removal level can be achieved under the action of the hydrodynamic effect. For the material is removed in elastic zone, no surface damage is occurred on the processed surface in HEP [6]. Meanwhile the material removal of the top position is higher than that of the other position, thus the...
surface become very smooth after HEP process. Therefore no defect and atomic level smooth surface can be easily achieved in HEP [7]. According to Ref.1, material removal mode of HEP can be expressed as:

\[
M_R(x, y) = \begin{cases} 
Cr(x, y) + C_1P(x, y) + e & \tau \geq \tau_{\text{min}} \\
0 & \tau < \tau_{\text{min}}
\end{cases}
\] (1)

Here \(C\) and \(C_1\) are positive constant related with the material, and \(r(x, y)\) and \(P(x, y)\) are the shear stress and hydrodynamic press on workpiece surface respectively.

However, HEP puts extremely high requirements on movement accuracy of the equipment, and the movement errors and the shape error of the wheel will directly affect the polishing effect. The tiny polishing marks on the processed surface are caused accordingly. The tiny marks will greatly influence the improvement of the surface quality. How to restrict the marks becomes very essential. Previous study shows that the introduction of wheel revolution can effectively eliminate the tiny marks under effect of homogenization. The polishing process will be complicated with the introduction of revolution movement. In this paper, 3D fluid dynamic simulation was introduced to analysis the influence of different HEP parameters in revolution-rotation condition.

![Figure 1. The principle of HEP.](image)

2. Establishment of the simulation model
The position where the polishing wheel comes into contacting with the surface of the workpiece is the main area where material removal occurs. This part is the focus area and requires a finer mesh. Considering the accuracy of the fluid simulation. However in terms of simulation efficiency, the mesh grid can’t be too detailed. For the smaller grid will lead to high performance requirements on the computer, computing time is too long. How to ensure the quality of the grid is a key issue in fluid dynamic simulation while taking into account the number of grids. Considering the end-relief effect that the fluid pressure will drop sharply beyond the width of the polishing wheel in the actual polishing process, shear stress is actually generated at area near wheel-workpiece surface where the polishing wheel is closest to the workpiece.
Under the premise of ignoring the weak interaction between the fluid and the air, we can simplify the actual physical model of 1:1 into the polishing area model, as shown in Figure 2(a). According to the characteristics of the symmetrical distribution of the flow field, the polishing area model is divided into two parts and reduced to a semi-polishing area model shown in Figure 2(b) and 2(c). Therefore the number of grids can be reduced for millions to about one million. At the same time, the grid where the gap is smallest can be refined to ensure the network. It improves quality of the grid and meanwhile reduces the number of grids. The model simplification process and meshing results are shown in Figure 2, respectively. The spherical crown wheel in the model has a diameter of 80mm and a width of 15mm. The previous research results show that the hydrodynamic pressure is mainly affected by the fluid shear force change in the effective processing parameter range [8]. The hydrodynamic pressure is not significantly affected by the change of the polishing wheel rotation speed and the wheel-workpiece clearance. Therefore, the main consideration of the simulation analysis in this paper is the variation of the shear stress on the surface under different working conditions.

### 3. Simulation results and analysis

#### 3.1. Influence of wheel-workpiece clearance

The shearing stress distribution of workpiece surface under different wheel-workpiece clearance was analyzed by Workbench Modules while the rotating speed of polishing wheel was fixed at a certain speed. The simulation result was shown in Figure 3. By comparison it can be found that the maximum fluid shear stress on the workpiece surface decreases with the increase of the clearance. The smaller the clearance is, the more sensitive the shear force is to the change of the clearance. After the clearance increases to a certain value, the shear stress is basically the same. No longer changes with the clearance, tend to a fixed value.

![Figure 2. Simulation modeling.](image)

![Figure 3. The relation between the wheel-workpiece clearance and the maximum shear stress.](image)
3.2. **Influence of the surface structure of the polishing wheel**

Shape errors and machining marks are inevitably caused on the polishing wheel during the manufacturing process. The effect of the processing waves on the polishing wheel is analyzed during the HEP polishing process. Figure 4 shows the observation of the surface structure of the wheel observed by a white light interferometer (Zygo NewView 700). It can be seen that there are periodic processing marks on the wheel surface. The period of the lines is about 5 μm, while the average amplitude is about 10 nm.

![Figure 4. Observation of the wheel surface by white light interferometer.](image)

3D Fluid dynamic simulation analysis was conducted to simulate whether this processing waves will affect the ultra-smooth surface machining. In the case of rotation, the processing marks on the polishing wheel will cause the periodic fluctuation of the fluid shear stress as shown in Figure 5. It can be known from Equation 1 that this disturbance will cause the processing marks on the wheel to be copied on the processed workpiece surface, resulting in fine polishing marks.

![Figure 5. The shear stress distribution on the workpiece surface under the wave wheel surface.](image)

3.3. **Influence of the wheel rotational error**

The wheel rotational error is influenced by the concentricity error, assembly error of the spinning shaft and roundness error. It is the radial bounce of the wheel during the HEP machining process. The bounce will cause the change of the wheel-workpiece clearance, which will affect the material removal efficiency and cause deterioration of surface quality of the workpiece. Although the impact of these errors can’t be avoided, we can minimize this effect from the technological point of view. As shown in Figure 6(a), \( O \) is the center of rotation of the polishing wheel, while \( O' \) is the geometric center and \( e \) is the eccentricity. We can see the change of the \( x \) length when the polishing wheel turns through \( \theta \) which is the position of the lowest point of the polishing wheel. Therefore it is change in the polishing gap. Through the derivation of the trigonometric function, we can get the solution:

\[
x = e \cos \theta + \sqrt{R^2 - e^2 \sin^2 \theta}
\]
Figure 6. The schematic of radical bounce of the wheel (a) Rotational error model (b) Radical bounce (c) Simulation model.

In HEP machining experiment, the raster scan is usually selected as the processing path. If the given scanning speed is 300 mm/min, the wheel rotation speed is set to 500 rpm. In other words, the polishing wheel rotates in the axial direction as 300/500 = 0.6 mm per revolution. We convert the above relation using the rotation angle as an independent variable to a polishing gap change with the axial position as an independent variable in the relationship of 0.6/(2π) = 0.0955, as shown in Figure 6(b) (Initial clearance setting to 20 μm). In this way, the rotation of the polishing wheel with radial bounce and the feed in the axial direction can be equivalent to the rotation of a cylindrical polishing wheel with a periodic texture on the surface, as shown in Figure 6(c).

The fluid dynamic simulation was conducted according to the above-mentioned equivalent model. The variation of shear force distribution on the workpiece surface at 200 rpm, 300 rpm, 500 rpm, 600 rpm, 1000 rpm, and 1500 rpm was explored, as shown in Figure 7. As the rotation speed increases, the periodicity of the shear force distribution on the workpiece surface becomes smaller and smaller. When the rotation speed increases to 1500 rpm, the scattering of peak shearing force due to the high point of the polishing wheel surface basically disappears. There is no clear separation between shear forces. In this way, ripples formed on the surface of the workpiece at a low rotational speed will be gradually converted into fine polishing marks by increasing the rotational speed, and the fine marks caused by the radial bounce and the cutter pattern can be homogenized by the revolution.

3.4. Influence of revolution speed
The revolution function can homogenize the disturbance of the fluid shear stress on the workpiece surface caused by the surface microstructure of the polishing wheel and the rotation accuracy of the polishing wheel. Thereby it can suppress the fine polishing marks to obtain an ultra-smooth machining surface. How the revolution speed is can be selected, and how does the introduction of the revolution affect the material removal characteristics? The hydrodynamic simulation was used to analyze the distribution of the shear force on the workpiece surface at different revolution speeds.

The simulation results are shown in Figure 8. The results show that as the revolution speed increases, the phenomenon of tailing and asymmetry become more serious. When the rotation speed exceeds 500 rpm, the shear stress becomes apparently asymmetrical. As mentioned earlier, the shape of the removal function of the polishing process is basically similar to the shape of the shear stress [9]. What we want to obtain is a regular shape, a symmetrical removal function, such as a Gaussian shape.
removal function. Therefore the smaller the revolution speed, the better is. On the other hand, the maximum value of the shear force remains basically unchanged. This is because the shear stress peaks are all distributed in the geometric center where the revolution speed is zero. The shear stress is generated by rotation, and the shear force is the same under the condition of the same rotation speed.

Figure 7. The shear stress distribution affected by radical bounce under different wheel speed.

Figure 8. The shear stress distribution affected by the revolution speed
4. Conclusions
According to the actual model of HEP, the material removal characteristics of the surface fluid under different working conditions of male revolution are analyzed and simplified. The material removal rate on the workpiece surface gradually decreases as the polishing clearance increases. The fine structure of the surface of the polishing wheel and the error of the rotation accuracy of the polishing wheel cause fine disturbance to the distribution of the shear force on the workpiece surface. It leads to fine polishing marks on the processed surface. Under the action of the revolution, the homogenization can be performed under disturbance, but the excessive revolution speed has an effect on the material removal stability. Therefore the revolution speed in the actual processing can’t be too large.

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