Research on simulation of abrasive belt polishing process for blade finishing

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Abstract. As the key part of energy power equipment of turbine, aircraft engines and so on, blade has high requirement on profile accuracy and surface quality. The abrasive belt polishing technology can ensure the profile accuracy and higher surface quality of the blade surface, and improve the blade processing efficiency. In this paper, the abrasive belt polishing process was analyzed by simulating single abrasive grain belt polishing process. The model of abrasive belt grain was constructed. The plastic finite element method was used to simulate the single abrasive grain polishing process. The simulation processing was determined according to the characteristics of blade abrasive belt polishing. The polishing process under different polishing parameters was simulated, and the variation curves of polishing forces of single abrasive grain under different polishing parameters were obtained. Based on the developed hybrid polishing machine tool for blade finishing, a testing system for abrasive belt polishing force was built. Through polishing experiments, the influence rule of polishing parameters on the polishing force of abrasive belt is obtained, and the correctness of the simulation is verified by the consistency of the rule.

1. Introduction

As one of the important finishing processes of complex free-form surfaces, polishing has a crucial impact on surface quality and has been investigated for decades. Recently, computer-controlled belt polishing has been introduced into precision manufacturing for its characteristics of flexibility, high-efficiency and labor liberation that make it very suitable for manufacturing workpiece with complex free-form surfaces[1,2]. In simulation, virtual modeling, kinematics simulation and static and dynamic performance simulation technology of abrasive belt polishing machine tool are becoming more and more mature. However, it is necessary to do more researches on simulation and parameter optimization technology of abrasive belt polishing process.

Over the years, many academics firstly made study on single abrasive grain belt polishing, and then indirectly analyzed the abrasive belt polishing process by mapping relationship between the single abrasive grain and the whole abrasive belt. Khellouki A established a three-dimensional abrasive model to determine the relationship between adhesive friction coefficient and plastic deformation friction coefficient, and used a single abrasive grain to show the abrasive belt polishing process[3]. Bucaille J L seted the workpiece of elastic material and plastic material respectively, carried simulation of the polishing with the tapered abrasive grain, and obtained the analysis and comparison of the polishing mark[4]. Jain R K studied the material removal rate and surface roughness of abrasive
grain under different pressures, and the material removal rate and surface roughness were pre-evaluated by using Finite Element software[5]. Chen X simulated the grinding wheel with spherical abrasive particles randomly distributed on the surface of the wheel, analyzed the grinding force[6]. Hegeman J B J W replaced the shape of the abrasive grain based on the theory proposed by Chen X, and simulated with ellipsoid instead of spherical abrasive grains[7]. Hou Z B established a probability model of the cutting height of abrasive grain according to the random distribution of abrasive grain on the effective surface of the abrasive, and the abrasive polishing process was simulated and predicted[8].

Based on the developed hybrid polishing machine tool for blade finishing, this paper establishes a single abrasive grain polishing simulation, and analyzes the influence rule of different polishing parameters on polishing forces, and verifies the simulation model by abrasive belt polishing experiments.

2. Simulation of single abrasive grain polishing

2.1. Preprocessing of simulation of single abrasive grain polishing process

2.1.1. Establishment of geometric model. Firstly, the model of abrasive grain and workpiece are established and STL files are generated in the three-dimensional modeling software CATIA. Then STL files are imported into the finite element software and simulation is made. In the simulation, the tool is an abrasive grain on the abrasive belt, and the workpiece is an ordinary engine blade.

According to the statistical characteristics of abrasive belt shape and the observation results of super depth of field three-dimensional microscopic system, the abrasive grain model is built as hexahedron. The cutting part of the abrasive grain is triangular pyramid, as shown in Figure 1. The geometric parameters of the abrasive grain model include the diameter $d$, the height $h$ and the top cone angle $\theta$. If the abrasive grain polishes along the right direction of X axis, $\alpha$ is the rake angle and $\beta$ is the rear angle. Most of the abrasive grains are obtained by the counter-roller machine, so the shape of the abrasive grains is flake like or sword like, and $h = 3d$.

In CATIA modeling, the abrasive belt polishing process is simplified as the abrasive grain moving a circular motion along with the contact wheel. The workpiece model is discretized with the plane as a unit.

2.1.2. Grid partition and material definition. The grid of workpiece is divided by relative grid. Under the condition that the maximum element boundary is twice the minimum element boundary, the workpiece is divided by a fixed number of grids. The grid is divided by tetrahedron element. The grid is refined in some places where the geometric change, strain and strain rate change greatly. The change weight is 0.5, the strain weight and the strain rate weight are both 0.25, and the three terms add up to 1. Relative value standard of 0.7 is adopted for grid re-division. The abrasive polishing process of single abrasive grain is very short, and the abrasive grains can be considered to have no abrasive wear during the abrasive polishing process.

The material physical model of workpiece is simplified as rigid viscoplastic model, and the workpiece is defined as a plastic body. In order to improve the simulation efficiency, the tool material is defined as a rigid body. The rigid body does not deform during the finite element simulation, so the tool material is not defined.

2.1.3. Establishment of the spatial position and motion parameters of the object. The spatial layout of tool and workpiece in the simulation of single abrasive grain polishing process is shown in Figure 2. In the tool movement option Speed is selected, and the abrasive grain is set to move in + X direction. In the tool rotation option Angular velocity is selected, and the abrasive grain is set to rotate around + Y axis. The workpiece is fixed on the lower firmware to limit its six degrees of freedom. The boundary condition of the workpiece is Velocity. The speed of X, Y, Z is set to 0, and the object motion control
in the Movement option must be set to 0. Firstly, the position of the abrasive grain on the tool when it cuts into the workpiece to reach the maximum polishing thickness of a single abrasive grain is determined by horizontal movement function, and then the contact wheel is rotated in the opposite direction of polishing through rotation function until the grain just breaks away from the workpiece. The abrasive belt polishing parameters are selected according to the process manual. The parameters of abrasive belt polishing in the simulation test are shown in Table 1.

![Figure 1. The geometric model of abrasive grain.](image1)

![Figure 2. The simulation spatial position of the single abrasive grain polishing.](image2)

**Table 1. The parameters of polishing.**

| Belt velocity (m/s) | Workpiece velocity (mm/s) | Polishing depth (mm) | Workpiece material | Grain size | Length×width (mm×mm) | Diameter of contact wheel (mm) |
|---------------------|---------------------------|----------------------|-------------------|------------|----------------------|-----------------------------|
| 8.64                | 1                          | 0.04                 | 45 steel          | P120       | 1150×5               | 46                          |

2.1.4. **Simulation algorithm and parameter selection.** The cutter is set as the main component, the interference value between workpiece and lower firmware is 0.0254, the friction between debris and abrasive grain is shear friction, the friction coefficient under the action of polishing fluid is 0.3, the external temperature is 20°C, the heat transfer coefficient between workpiece and outside is 45N/sec/mm/C, the convective heat transfer coefficient is 0.02, and the other parameters are the default values of the system. The rigid-plastic finite element equation is established by Lagrange equation. The Conjugate-Gradient method is chosen as the finite element method. The direct iteration method is chosen as the iteration method, and the time when the abrasive grain pass through one third of the length of the element is chosen as the iteration condition. Since the minimum unit length of the workpiece is 0.005mm, the time taken for the abrasive grain to pass through this distance is 1.9e-07sec, and the total number of iterations is 700 steps, and every 10 steps are stored, which can prevent simulation errors and unexpected stops from affecting the simulation process.

After completing the above steps, data packets are generated and simulated.

2.2. **Post processing of single abrasive grain polishing process**

2.2.1. **Geometric simulation of single abrasive grain polishing process.** Figure 3(a) shows abrasive debris formed by oblique cutting with abrasive grain, and Figure 3(b) shows the surface morphology of the workpiece after polishing with a single abrasive grain.
2.2.2. Numerical simulation of single abrasive grain polishing process. The curves of tangential and normal polishing force of a single abrasive grain in the polishing process are shown in Figure 4, while the axial polishing force is neglected because it is small.

![Curves of tangential and normal polishing forces of a single abrasive grain](image)

**Figure 4.** Curves of tangential and normal polishing forces of a single abrasive grain.

Heat and time are introduced into the stress solution equation of plastic finite element method, which will inevitably lead to the variation of polishing force. The polishing force of a single abrasive grain with force-heat coupling is studied by the post processing function of finite element software. It can be seen from Figure 4 that the polishing force of the abrasive grain cutting into the workpiece during the ruling stage is produced by the plastic deformation, and then the polishing force begins to increase in the cutting stage. The polishing depth increases with the increasing of polishing time, so the polishing force continues to increase with the increasing of the polishing depth until the polishing force reaches the maximum value, and then the polishing force decreases with the polishing depth. The force gradually decreases, until the abrasive grain cut out of the workpiece and the polishing force becomes zero. The whole polishing process is generally symmetrical before and after reaching the maximum polishing depth.

2.3. Simulation of influencing factors on single abrasive grain polishing force

2.3.1. Single factor polishing simulation test. The abrasive process is respectively simulated with abrasive belt velocity, workpiece velocity, abrasive belt polishing depth and workpiece material hardness as variables. The abrasive parameters are shown in the table 1. Eight tests were made for each group of variables, and 56 single abrasive grains were simulated. The simulation data curve was obtained and the abrasive force was obtained after data processing. In this paper, the simulation data is processed by using MATLAB. The relationship between different polishing parameters and single abrasive grain polishing force is shown in the Figure 5—Figure 8.
2.3.2. Multi factors polishing simulation test. The polishing process is simulated by choosing abrasive grain size and polishing depth as variables. Corundum abrasive belts with grain size of P80, P120, P180 and P220 are selected to simulate under different polishing depth conditions. Eight tests are carried out for each kind of abrasive belt. The other parameters of polishing are identical to that of Table 2. The relationship between polishing force and polishing depth are shown in Figure 9 and Figure 10.
3. Polishing experiments

3.1. Experiment of Influence factors on abrasive belt polishing force

In order to verify the accuracy of single abrasive polishing process simulation, the polishing experiment is carried out on the basis of the new series hybrid polishing machine tool for blade finishing developed by the research group.

The abrasive belt polishing force measurement system is shown in Figure 11. Kisteler-9257B quartz dynamometer is used as the force testing element. The fixture installed on the moving platform of the machine tool. The charge signal collected by the dynamometer is transmitted to the charge amplifier through the connecting wire, and then the voltage signal after conversion is transmitted to the computer with A/D board for processing. The real-time and accurate three-dimensional polishing force of the abrasive belt polishing machine tool is obtained.

The polishing forces in three directions \(F_x\), \(F_y\), \(F_z\) on the dynamometer are processed by the system software. During the measuring process, the values fluctuate at zero and the amplitudes are less than 0.1N, which provides experimental data support for neglecting the axial polishing force in the simulation. The mechanism of abrasive belt polishing shows that the tangential polishing force \(F_t\) is not same as \(F_y\), and the normal polishing force \(F_n\) is not the same as and \(F_z\). But \(F_t\) can be replaced by \(F_y\), and \(F_n\) can be replaced by \(F_z\) because the polishing depth is very small, and the angle between \(F_t\) and \(F_y\), and between \(F_n\) and \(F_z\) is approximately zero.

3.2. Experimental results of Influence factors on abrasive belt polishing force

The P120 corundum abrasive belt is selected to polish the 45 steel workpiece. The contact wheel was a 46 mm rubber wheel with 0.04mm polishing depth and 1mm/s workpiece velocity. The force measurement experiments were carried out under the conditions of respectively 5 m/s, 7.5 m/s, 10 m/s, 12.5 m/s and 15 m/s belt velocity. The experimental results are shown in Figure 12.

The belt velocity is 8.64 m/s, the workpiece velocity is respectively 1.2 mm/s, 1.6 mm/s, 2 mm/s, 2.4 mm/s and 2.8 mm/s, and other parameters are unchanged. The force measurement experiments are carried out under conditions above, and the experimental results are shown in Figure 13.
The belt velocity is 8.64 m/s, the workpiece velocity is 1 mm/s, the polishing depth is respectively 0.02 mm, 0.03 mm, 0.04 mm, 0.05 mm and 0.06 mm, and other parameters are unchanged. The force measurement experiments are carried out under conditions above, and the experimental results are shown in Figure 14.

**Figure 13.** The relationship between workpiece velocity and belt polishing force.  
**Figure 14.** The relationship between polishing depth and belt polishing force.

4. Conclusions
In order to meet the requirement of high efficiency and high precision, the blade belt polishing process is adopted. The simulation of single abrasive grain polishing process is carried out. The geometric and numerical simulation of single abrasive grain polishing process is carried out by using plastic finite element method. The dynamic geometric simulation is used to reproduce the polishing process. The characteristic curve is obtained by denoising. Through the polishing simulation test, the curve of single abrasive grain polishing force under the influence of different polishing parameters is obtained. The test system of abrasive belt polishing force is constructed. The influence rule of abrasive belt velocity, workpiece velocity and polishing depth on abrasive belt polishing force is obtained by experimental data, and the accuracy of single abrasive grain polishing process simulation is verified.

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