Development of Decoupling Device for Vibration-Assisted Roller Polishing of Silicon Carbide Ceramics

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ABSTRACT For the research of the performance of vibration-assisted roller polishing (VARP) on the silicon carbides (SiC), a new decoupling device was designed. By introducing the fully symmetrical structure and the double parallel four-bar mechanism, the movement in the X and Y directions is decoupled. The dynamic and static characteristics of the device are analyzed using finite element analysis. Testing experiments were conducted to investigate the actual performance of the developed device. The results show that the coupling rate of the x-axis and y-axis are about 1.6% and 1.4%, respectively. The working space of the device is about 38 µm x 42 µm, and the natural inherent is about 1198Hz. In addition, a VARP force model for SiC was established to help scientifically understand the removal mechanism. The polishing experiments are carried out to verify the feasibility of the model and the effectiveness of the device. The experimental results show that the maximum error between the model results and the measured force is about 7.7%. As the amplitude and frequency of the device increase, the surface roughness of the SiC decreases from 168nm without vibration to 54nm and 47nm, respectively.

INDEX TERMS Decoupling device, vibration-assisted roller polishing, silicon carbide, polishing force, surface roughness.

I. INTRODUCTION

Silicon carbide (SiC) ceramics have been generally used in semiconductor, aerospace, and optical as possess excellent material properties (e.g., high chemical stability, extreme hardness, and high heat stability [1]–[3]). Generally, optical components are ground and polished to meet quality requirements [4]. However, due to the direct hard contact between the tool and workpiece, process-induced irregularities and defects on the workpiece surface such as deep scratches, pits, micro-cracks, and subsurface damage may occur in traditional polishing processes [5]. Therefore, there is an urgent need to develop a mature and effective SiC processing technology.

Considering the processing characteristics of SiC, vibration-assisted processing is used as a hybrid manufacturing technology in the processing of SiC, which combines precision machining with the vibration of the tool (or workpiece) [6]. To further improve the processing efficiency and reduce the fracture damage of the large SiC workpiece, polishing rollers are selected as processing tools [7], [8]. There are two working modes of vibration-assisted processing: resonance mode and non-resonant mode. The resonant vibration-assisted processing device is driven by an actuator and vibrates at a resonant frequency. Suzuki et al. [9] synthesized two different vibrations at the polishing head by combining a disc-shaped piezoelectric actuator and a pair of semi-disc-shaped actuators. Yin et al. [10] developed a new type of ultrasonic vibration device based on the complex-beam horn structure, which requires only a single drive to achieve elliptical motion. Lin et al. [11] used...
flanges and spring retainers to connect the main body of the ultrasonic device with the protective shell, and adjusted the pre-tightening force of the flange and the shell to make the main body of the ultrasonic device have a rotating function. Although the ultrasonic vibration-assisted processing device has a high energy utilization rate, it is difficult to adjust the vibration parameters and processing trajectory flexibly.

To solve above problem, the linear piezoelectric platform has been proposed as a non-resonant vibration-assisted motion device to improve processing flexibility. However, the working space of the platform is limited by the nominal stroke of piezoelectric actuators (PZTs). The lever mechanism and bridge mechanism as commonly used magnifying mechanisms have been applied to piezoelectric platforms to solve the problem of working space [12], [13]. Although these platforms can have a larger working space, there is a problem that the stiffness of these platforms is also significantly reduced [14]. The lower stiffness will not only lead to susceptibility to external interference during processing, but also reduce the inherent frequency of the platform. Therefore, Polit and Dong [15] developed a high-rigidity platform by applying a parallelogram hybrid elastic mechanism. However, the working space of the platform is too small, and the flexibility of the processing process is relatively poor. To increase the flexibility of the platform, the rotating mechanism is used in the platform [16], [17]. Meanwhile, the developed platforms have the problem that the motion trajectory is difficult to control. Based on the limitations of the above platforms, it is necessary to develop a novel 2-DOF vibration-assisted polishing device for the VARP process. The device has a high natural frequency, sufficient vibration amplitude, and low coupling rate, which can achieve accurate motion trajectories that meet the requirements of VARP processing.

The theoretical model of processing force prediction provides an effective tool for optimizing process parameters, which helps to research the removal mechanism and guide the actual processing. Based on the Werner model, Li et al. [18] developed a novel grinding force model, which considered chip formation and friction during machining. In addition, the ratio of tangential and normal forces was analyzed. Younis et al. [19] extended Li’s work by using a combination of ploughing, friction, and chip formation forces to build a grinding force model. Li and Liao [20] calculated the effective cutting point and grinding force of a single abrasive particle when grinding a ceramic with a diamond wheel. Zhao and Chang [21], [22] combined Hertzian contact theory with Greenwood and Williamson (G&W) elastic contact theory to calculate the actual contact area of (chemical mechanical polishing). In addition, through the two force balance theories, the penetration depth of single abrasive particles in CMP was calculated. Patnaik Durgumahanti et al. [23] considered the influence of different friction coefficients and plow forces on the grinding force model, and determined them through single factor experiments and the single-grit scratch tests. To guide the process of the ultrasonic-assisted internal grinding, Cao et al. [24] established a mathematical model of grinding force and concluded that vibration can reduce the internal grinding force. Lu et al. [25] explored the number of effective abrasive grains during processing during the establishment of an internal microtopography prediction model for dual-axis wheel polishing. In summary, most of the existing related models were developed for predicting grinding force and traditional polishing force, which cannot be directly applied to VARP polishing force prediction. Therefore, it is necessary to develop a polishing force model for the VARP of SiC to analyze the processing effect and guide the actual processing.

To scientifically research the removal mechanism and guide the actual polishing of SiC, this article proposed a decoupled 2-DOF non-resonant polishing device (DN-VPD) and developed a comprehensive polishing force model. Different from the previous linear piezoelectric device, the DN-VPD developed in this article can not only ensure that the performance can meet the requirements of the VARP process, but also ensure the accuracy of the vibration trajectory by introducing the flexible guide mechanisms. The accurate vibration trajectory can improve the prediction error of the polishing force model and the actual processing effect. The comprehensive polishing force model not only considers the abrasive particle distribution of the VARP process and the motion trajectory and performance of the DN-VPD, but also combines the three abrasive particle-workpiece contact forms of chip formation, friction, and plough. In addition, the device tests and polishing experiments are carried out to verify the validity and feasibility of the DN-VPD and the proposed model, and the effects of vibration parameters on polishing force, roughness, and surface morphology are analyzed. The vibration-assisted roller processing method is proposed in the section II. The design idea, simulation, and performance test of the DN-VPD is shown in the section III. A machining force model based on the motion performance of the DN-VPD and the machining mechanism of roller polishing is developed in the section IV. In the section V, the experiments are carried to verify the validity of the developed DN-VPD and the established processing force model. The conclusions of the work are summarized in the section VI.

II. VIBRATION-ASSISTED ROLLER POLISHING PROCESS

Fig. 1 briefly describes the VARP process. The VARP system is mainly composed of a DN-VPD and roll-type polishing machine. The polishing roller is mounted on the couplings to produce rotary motion through numerical control. The DN-VPD which is carried on the dynamometer (as shown in Fig. 1(a) and (b)) is driven by two piezoelectrics (PZTs) that receive open-loop control signals from the signal generator. When the rotary motion of the roller, the non-resonant plane vibration trajectory of the carried workpiece are generated at the same time, the VARP system is performed.

The polishing tool used in this study is a cylindrical 7075 aluminum alloy roller which is covered by a polyurethane polishing layer (Fig. 1(c)). As shown in Table 1, the dimensions and material parameters of the polishing pad
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FIGURE 1. Illustration of the VARP process: (a) Physical photos of the VARP process, (b) Schematic diagram of the VARP process, (c) Polyurethane polishing pad and (d) Physical photos before and after VARP polishing.

TABLE 1. The dimensions and material parameters of the polishing pad and polishing roller.

| Parameter                  | Value |
|----------------------------|-------|
| Density (Kg·m⁻³)           | 491   |
| Poisson’s ratio            | 0.47  |
| Modules of elasticity (MPa)| 41.40 |
| Thickness (mm)             | 2     |
| Shore A hardness           | 73    |
| Polishing pad Width (mm)   | 120   |
| Polishing roller Radius (mm)| 23   |

and polishing roller are listed. Diamond particles with an average particle size of 1 µm were selected for practical polishing. Finally, the surface of the original SiC workpiece and the SiC workpiece after VARP processing are shown in Fig. 1(d).

III. DESIGN OF DEVICE

A. STRUCTURAL DESIGN OF THE DN-VPD

To meet the amplitude requirements of the VARP system, the lever mechanism with the advantages of a small structure [26] and the magnification ratio is used in the DN-VPD. Although the lever magnifying mechanism can achieve a good magnification rate, the flexural output displacement that is unavoidable when the lever magnifying mechanism moves around the fulcrum. Therefore, the symmetrical structure with the lever-amplifying mechanism is combined in this article. It offsets the coupling motion through the symmetrical flexural motion to ensure the output displacement direction along the centerline [27], as shown in Fig. 2.

However, the idea of completely canceling the coupled motion through symmetrical flexural motion is too ideal. Therefore, the compound parallelogram mechanism is used in all directions to realize the guiding function. The structure and movement mechanism of the compound parallelogram mechanism is shown in Fig. 3. This mechanism is a classic guide mechanism, which can significantly inhibit the coupling movement of the DN-VPD.

After selecting and analyzing the hinge shape and mechanism size for conduction, the DN-VPD driven by PZT is proposed, as shown in Fig. 4. To further reduce the coupling rate, the output-end outside the center platform is the same structure as the input-end. The right circular flexure hinges are selected for the fulcrum and input end of the lever because they are more suitable for forming a flexural movement. The P-joints are applied to double parallel four-bar mechanisms because they are more suitable for stretching. The PZTs are used to actuate the input-end of the DN-VPD, and then the displacement amplifiers magnify the input displacement. Meanwhile, the symmetrical structure limits the undesired motions of the DN-VPD. Considering the fixing problem, pre-tightening bolts are used to fix the PZTs. In addition, the structural size of the device is optimized using the gray wolf optimization algorithm [7].
was 7075 aluminum (7075AL), the density of the material was 2810 kg/m³, the elastic modulus is 71700Mpa, and the Poisson’s ratio is 0.33.

To prevent failure and deformation of the DN-VPD during continuous operation. It is necessary to ensure that the maximum stress of DN-VPD is less than the yield strength of 7075AL (the ratio of yield stress to safety factor). The yield stress of 7075AL is 503MPa, and the safety factor selected in this article is 2. Therefore, the movement of DN-VPD is simulated under the maximum input force of PZT (F₁ = 1300 N). The simulation result shows the maximum stress state of the DN-VPD in the extreme state of motion, as shown in Fig. 5. The maximum stress of DN-VPD in the extreme motion state occurs on the straight beam hinge of the guide mechanism, and its value is about 240.6MPa. The simulation results verify that the maximum stress is lower than the yield strength of the material, and the developed DN-VPD can meet the working requirements.

B. FEA SIMULATION OF THE DN-VPD

To ensure that the DN-VPD can meet the processing requirements, the prototype structure of the DN-VPD was established. The Hypermesh software (Altair Inc.) was used to divide the 3D model of the DN-VPD using the method of pentahedral mesh assisted hexahedral mesh. The divided 3D model had 108,785 grids. To make the simulation results closer to the actual processing performance, only the screw hole part of the DN-VPD connected with the machine tool was completely restricted in the process of setting the boundary. The finite element simulation software ABAQUS (3Ds Dassault Systems Inc.) was used to simulate and analyze the dynamic and static performance indicators of the DN-VPD, such as maximum stress, stiffness, coupling rate, working space, and modal. To improve the accuracy of analysis, the hexahedron element was chosen. During the simulation analysis, the material used in the DN-VPD and the study was 7075 aluminum (7075AL), the density of the material was 2810 kg/m³, the elastic modulus is 71700Mpa, and the Poisson’s ratio is 0.33.

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To confirm the accurate stiffness and coupling ratio of the DN-VPD, the linear input force of 0-1300N is applied to the x-axis and y-axis input ends of the DN-VPD. The output displacements of the x-axis and y-axis at the output ends of the DN-VPD are collected. As shown in Fig. 6, when the x-axis input force is 1300N, the x-axis output displacement is about 78. µm, and when the y-axis input force is 1300N, the y-axis output displacement is about 80µm. To further ensure the accuracy of the simulated stiffness, the force-displacement curves of the DN-VPD are shown in Fig. 7.
The simulation results show that the output displacement increases linearly with the increase of the input force. After calculation, it can be concluded that the stiffness of the x-axis is about 16.69N/µm, and the stiffness of the y-axis is about 16.29N/µm. In addition, the force-coupling ratio curve of the DN-VPD can be obtained from Fig. 7. The simulation results show that the coupling rate of the x-axis is about 1.579%, and the coupling rate of the y-axis is about 1.58%. The coupling rate of DN-VPD can meet the requirements of the VARP process.

However, the working space of the DN-VPD is not only limited by the maximum thrust of the PZT, but also by the rated stroke of the PZT. To confirm the maximum stroke of DN-VPD in actual work, the 32µm (the rated stroke of the PZT) is chosen as the input displacement to be applied to the x-axis and y-axis input ends of the DN-VPD. As shown in Fig. 8, when the input end of the x-axis of the DN-VPD receives input displacement, the output end will produce an output displacement of 42.3µm. When the input end of the y-axis of the DN-VPD receives input displacement, the output end will produce an output displacement of 42.8µm. Compared with the working space (78.1µm × 80µm) produced by the input force of 1300N, the working space produced by the input displacement of 32µm is lower. Therefore, the working space of the DN-VPD should be 42.3µm × 42.8µm. The working space of the simulated DN-VPD can basically meet the processing requirements of VARP.

Modal analysis is applied to determine the resonant frequency of the DN-VPD. As shown in Fig. 9, the first four modes of the DN-VPD are obtained, and the resonant frequencies of the modes are recorded in Table. 2. The movement produced by the first two modes is in the plane, and the latter two modes produce three-dimensional movement. Since the frequency of the last two modes is much higher than the resonance frequency of the first mode, the actual motion of the DN-VPD will not be affected by the three-dimensional motion mode. To further ensure that the actual processing trajectory is not affected by the resonance phenomenon, the frequency below 1206.5 Hz (the frequency of the first mode of DN-VPD) is selected for processing.

C. PROTOTYPE FABRICATION AND EXPERIMENTS OF THE DN-VPD

In this section, a prototype of the DN-VPD is manufactured, and the testing experiment is carried out to confirm the property of the DN-VPD.

1) PROTOTYPE FABRICATION OF THE DN-VPD

As shown in Fig. 10, the DN-VPD is manufactured by the wire cut electrical discharge machining from a piece of AL7075 material, which has a higher yield strength and elastic modulus than AL6061-T651 material.

2) EXPERIMENTAL SETUP

As a controller, the Power PMAC can accurately provide and receive output signals. The actuating signals were magnified by the power amplifier (E-500, PI Inc.) and then applied on two PZTs (model 40vs12 with the nominal displacement of 32µm, static large-signal stiffness of 35N/µm, and a maximum driving force of 1300N) to achieve micromotion. To acquire the displacement signals of the DN-VPD, double signal–probe capacitive displacement sensors

![FIGURE 7. Output displacement and coupling rate under input force test simulation.](image)

![FIGURE 8. Simulation of input displacement(32µm) test: (a) x direction; (b) y direction.](image)

![FIGURE 9. The simulation of frequency response test.](image)

| Modes | 1st | 2nd | 3rd | 4th |
|-------|-----|-----|-----|-----|
| Frequency(Hz) | 1206.5 | 1206.9 | 1238.9 | 1789.5 |

TABLE 2. The resonance frequency of the vibration-assisted mechanism.
(2805, MicroSense Inc.) and a multi-channel position measurement system (DE 5300-013, MicroSense Inc.) were selected in this system. The displacement output by the DN-VPD is transmitted to the displacement sensor by the partition plate fixed on the center platform by screws. The output motion signals pass to Power PMAC and act as feedback signals to form closed-loop control. In this article, the pre-tightening deformation of the DN-VPD is collected by the displacement sensor. Through many inspections and processing experiments, it is found that the pre-tightening displacement of $\mu$m can meet the pre-tightening demand of piezoelectricity. When the pre-tightening deformation is $\mu$m, the output of the DN-VPD will not have too much influence, and it can ensure that the PZTs will not fall off during processing and test. To reduce the experimental error, the testing experiments were executed on the platform at room temperature ($25^\circ$C). The complete testing experiment setup is shown in Fig. 11.

3) DYNAMIC TEST OF THE DN-VPD

In this section, the sine sweep frequency excitation signal is selected to explore the inherent frequency of DN-VPD. The 100Hz to 3000Hz sine frequency sweep signal is applied to the PZTs on the x and y axes, respectively. The output displacement can be collected by a capacitance sensor. Then, the fast Fourier transform is performed on the acquired displacement-time signal in MATLAB software to obtain the displacement-frequency response. For the displacement-frequency response curve, the first peak of the image is the inherent frequency of the DN-VPD. As shown in Fig. 12, the first frequency peaks in the x and y directions are about 1198 Hz and 1198 Hz, respectively. Since the x and y axes have the same structure, they obtain the same natural frequency after being excited, respectively. Compared with the simulation results, the experimental results are reduced by about 8.5 Hz, and the two are in good agreement. As a non-resonant polishing device, the operating frequency is limited by the inherent frequency of the DN-VPD. The DN-VPD with the inherent frequency of 1198Hz can meet the precision polishing requirements of VARP.

4) STROKE TEST OF THE DN-VPD

As we all know, the larger working space of VARP can improve flexibility and processing efficiency. Therefore, a closed-loop test experiment was conducted on the DN-VPD to obtain the feedback data of the VARP output displacement in this article. The stepping signals with a maximum of 42$\mu$m and 48$\mu$m were applied to the PZTs of the x-axis and y-axis of the DN-VPD, respectively. Among them, “Response” means “measured displacement signal” and “Command” means “command displacement signal”. The test results show that the maximum stroke of the x-axis can reach approximately 38 $\mu$m, and the maximum stroke of the y-axis can reach approximately 42 $\mu$m, as shown in Fig. 13. Compared with the simulation result, the actual measurement result of the x-axis is reduced by about $\mu$m, the actual measurement of the y-axis is basically the same, which is due to the machining error and the friction in the test process. The DN-VPD with a working space of 38 $\mu$m × 42 $\mu$m can meet the precision polishing requirements of VARP.
5) COUPLING TEST OF THE DN-VPD

The DN-VPD with a low coupling rate can provide an accurate vibration trajectory. A low-frequency sinusoidal signal with a frequency of 0.67 Hz and an amplitude of 10 µm is applied by PMAC to excite a PZT to apply an input displacement in the main movement direction. The displacement generated by the main movement direction with displacement input and the secondary movement direction without displacement input is collected by the displacement sensor. The coupling ratio is calculated by comparing the coupling displacement produced by the secondary movement direction and the displacement produced by the main movement direction. As shown in Fig. 14, the coupling displacement in the X direction is about 0.165 µm, and the motion coupling in the X direction is about 1.6% of the main motion generated in the Y direction. The coupling displacement in the Y direction is about 0.138 µm, and the kinematic coupling in the Y direction is about 1.4% of the main motion generated in the X direction. Compared with the simulation results, the x-axis test result is basically the same, and the y-axis test result is reduced by about 0.2%, which is caused by machining errors and testing. In addition, two sets of sine signals with a phase difference of π/2 are applied to the PZTs of the two axes at the same time to test the actual motion trajectory, as shown in Fig. 15. The test results show that the parasitic motion generated by the dual axis hardly affects the vibration trajectory of the DN-VPD.

IV. POLISHING FORCE ANALYSIS

In this section, a polishing force model of the VARP process is established.

A. ASSUMPTIONS

According to the study of Zhao’s research [22], the material removal process during the polishing process is an interference action that occur at the polishing contact area which locates between the abrasive grains and the workpiece surface. To research the impacts of process parameters on polishing force during VARP, the following assumptions should be taken into consideration before establishing the model:

a) The shape of the abrasive particles is assumed to be spheres with a fixed diameter. In addition, under the action of the polishing pad and the pressure, the active abrasive particles are evenly embedded in the workpiece.

b) Since the three-body wear is not obvious compare to the two-body wear, it is supposed that the effective numbers of the abrasive particles are completely inlaid in the polishing pad.

c) Considering the penetration depth of the VARP process, the removal behavior can be assumed as a plastic removal.

B. REMOVAL MECHANISM OF THE VARP

During the VARP process (Fig. 16(a)), there will be an instantaneous contact area between the rough polishing pad surface and the smooth SiC surface under pressure $F$ (Fig. 16(c)). Fig. 16(b) and (f) respectively show the macroscopic contact form (Hertz contact) and mesoscopic contact (G&W elastic contact) of the contact area. Fig. 16(d) shows the relationship between pad, abrasive, and workpiece during processing. The active polishing particles in the contact area remove the workpiece material by plowing and cutting on the workpiece under the action of the processing speed (Fig. 16(e)).

1) MOTION TRAJECTORY OF ABRASIVE GRAINS IN THE VARP

The movement of the crystal grains comes from the frequency ($f$), amplitude ($A$), and phase difference ($\phi$) of the DN-VPD, the speed of the polishing roller ($n_0$), and the feed speed ($v_f$). Therefore, the ideal equations of motion and velocity...
of individual abrasive particles are derived as follows:

\[
\begin{align*}
\mathbf{s}_g(t) &= \begin{pmatrix} x_g(t) \\ y_g(t) \\ z_g(t) \end{pmatrix} = \begin{pmatrix} \nu_f t + A \cos(2\pi ft) \\ R_0 \sin(2\pi n_0 t) + A \sin(2\pi f + \varphi) \\ R_0 \cos(2\pi n_0 t) \end{pmatrix} \\
\mathbf{v}_g(t) &= \mathbf{s}_g'(t) = \begin{pmatrix} x'_g(t) \\ y'_g(t) \\ z'_g(t) \end{pmatrix} = \begin{pmatrix} v_f - 2\pi f A \sin(2\pi ft) \\ 2\pi n_0 R_0 \cos(2\pi n_0 t) + 2\pi f A \cos(2\pi ft + \varphi) \\ -2\pi n_0 R_0 \sin(2\pi n_0 t) \end{pmatrix}
\end{align*}
\]

\[1\]

\[
\begin{align*}
\text{where } R_0 \text{ is the radius of the roller and } t \text{ is the unit time, in this article } t = 0.01s. \text{ The simulated trajectories of individual abrasive particles with different phase differences are shown in Fig. 17. Since the simulation results show that the phase difference has a small effect on the abrasive grain trajectory, the influence of the phase difference on the polishing experiment is not considered in this article.}
\]

\[2\) CONTACT AREA OF POLISHING PAD-WORKPIECE INTERFACE IN THE VARP

The macroscopical theoretical contact area \((A)\) of the VARP process can be derived from the Hertzian contact theory [28], as shown in Fig. 16(b). The half width \((a)\) of the macroscopical theoretical contact area can be derived as

\[
\begin{align*}
a &= \left[ \frac{2}{\pi b} \left( \frac{1 - v^2_p}{E_p} + \frac{1 - v^2_w}{E_w} \right) \right]^{1/2} \sqrt{F} \\
A &= (2a + l_c) \times b \\
&= \left[ \frac{8b}{\pi} \left( \frac{1 - v^2_p}{E_p} + \frac{1 - v^2_w}{E_w} \right) \right]^{1/2} \sqrt{F} + l_c b
\end{align*}
\]

\[3\] and \[4\]

where \(l_c\) is the distance the polishing roller rotates per unit time. \(E_p\) and \(E_w\) are the elastic modulus of the polishing pad and workpiece, respectively. \(v_p\) and \(v_w\) are the Poisson's ratio of the polishing pad and workpiece, respectively.

As shown in Fig. 16(f), due to a large number of concave holes on the surface of the polyurethane (polishing pad material), the contact between the polishing pad and the workpiece can be approximated by a rough surface contacting with a smooth surface. Due to the polishing pad has high surface compliance, the contact between the pad-workpiece surfaces can be considered elastic. Furthermore, G&W elastic model is applied to calculate the micro-contact between pad and workpiece surface. The entire actual contact area \((A_s)\) are
FIGURE 17. The trajectory of a single abrasive particle with different phase differences: (a) $\phi = 0$, (b) $\phi = 45^\circ$.

-derived as [29]

$$A_s = C_0^{-1} \left( \frac{\beta_0}{\sigma_p} \right)^{\frac{1}{2}} \frac{L}{E_{pw}} = C_0^{-1} \left( \frac{\beta_0}{\sigma_p} \right)^{\frac{1}{2}} pA$$

where $C_0$ is a dimensionless coefficient. According to Qin et al. [30], the value of $C_0$ ranges from 0.4 to 0.5. $\beta_0$ is the average radius of curvature of the protrusions of the polishing pad. $\sigma_p$ is the standard deviation of the peak height size distribution of the protrusion. $p$ is the average pressure. $E_{pw}$ is the abrasive-polishing pad composite elastic modulus.

3) NUMBER OF EFFECTIVE ABRASIVE PARTICLES

During VARP processing, material removal is produced by abrasive particles dispersed in the polishing slurry, assuming that the volume distribution of the abrasive particles in the contact region is uniform and equal to the volume distribution within the polishing slurry, as shown in Fig. 16(f). The relationship between the number of particles per unit length of the linear distribution density $l$ and the volume density $\chi$ of the polishing liquid can be shown as:

$$l^3 \xi = \chi$$

where $\xi$ is the average volume of a single abrasive grain,

$$\xi = \frac{1}{6} \pi D^3$$

Substituting (6) into (7) and rearranging

$$l = \left( \frac{6\chi}{\pi D^3} \right)^{1/3}$$

Due to the areal concentration $q$ of the abrasive particles is connected with the linear density $l$

$$q = l^2$$

According to (8) and (9), the number of abrasive particles involved in material removal during polishing can be derived as

$$N_a = A_s q = A_s \left[ \frac{6\chi}{\pi D^3} \right]^{2/3}$$

4) AVERAGE PENETRATION DEPTH OF SINGLE ABRASIVE PARTICLES

The penetrate depth of the polishing particles during VARP processing is also an important variable affecting the polishing force. Considering the discrepancy in mechanical properties between the polishing pad and the workpiece, when polishing particles are compressed, the polishing pad and wafer typically experience different deformation modes, as shown in Fig. 18. Combining the force balance of the polishing particles during processing can determine the penetration depth of the polishing particles. And the contact force of the polishing particles and the polishing pad is given by

$$F_{sp} = \frac{4}{3} E_{sp} R^{1/2} \delta_p^{3/2}$$

where $R$ is the radius of the abrasive grain, $E_{sp}$ is the abrasive-polishing pad composite elastic modulus, $E_{sp} = \frac{4}{3} \left( \frac{1-v_s^2}{E_s} + \frac{1-v_p^2}{E_p} \right)^{-1}$, $v_i$ and $E_i$ are the Poisson’s ratio and the Young’s modulus $i$ ($i = s$ or $p$) of the abrasive grain and the polishing pad, respectively.

In addition, the plastic contact force between the abrasive particles and the workpiece can be written as

$$F_{sw} = H_w \pi D \delta_s$$

Based on the principle of force balance, the following equation can be obtained [22]

$$2H_w \pi R \delta_s = \frac{4}{3} E_{sp} R^{1/2} \delta_p^{3/2}$$

Furthermore, the depth of the indentation of individual particles into the pad-workpiece surface is related to the
diameter of the abrasive particles.

\[ \delta_p + \delta_s = D = 2R \]  

Combine and rearrange (13) and (14)

\[ \delta_s^3 + \left( \frac{9H^2 \pi^2 R}{4E^2 p} - 6R \right) \delta_s^2 + 12R^2 \delta_s - 8R^3 = 0 \] (15)

C. DEVELOPMENT OF POLISHING FORCE MODEL

Under ductile conditions, chip formation force, ploughing force, and friction force constitute the polishing force.

Then, the entire polishing force \( F_{SG} \), normal force \( F_n \), and tangential force \( F_t \) can be written respectively as

\[ F_{SG} = F_{chip} + F_{plough} + F_{friction} = \sqrt{F_n^2 + F_t^2} \] (16)

\[ F_n = F_{nc} + F_{np} + F_{nf} \] (17)

\[ F_t = F_{tc} + F_{tp} + F_{tf} \] (18)

where \( F_{nc} \) and \( F_{tc} \) are the normal and tangential components of chip formation force, respectively. \( F_{np} \) and \( F_{tp} \) are the normal and tangential components of frictional force, respectively. \( F_{nf} \) and \( F_{tf} \) are the normal and tangential components of plough force, respectively.

1) CHIP FORMATION FORCE

Since the cutting action of a single polishing particle during the polishing process is similar to that of turning, the normal component of the chip formation force generated by a single polishing particle can be assumed to be a function of the cross-sectional area of the undeformed chip [18].

\[ F_{nc}' = K_1 Q_i \] (19)

The normal chip forming force of all active particles in the contact area of polishing pad and workpiece constitutes the entire normal chip formation force of polishing unit width [18]

\[ F_{nc} = \sum K_1 Q_i = K_1 \sum Q_i \] (20)

where \( \sum Q_i \) is the entire area of the chip section generated simultaneously by all active abrasive particles per polishing width, which is given as [18]

\[ \sum Q_i = \frac{v_w}{v_c} \delta_s \] (21)

where \( v_w \) is the combination of feed speed, \( v_w = v_f \), and \( v_c \) is the rotational speed of the polishing roller and vibration speed.

\[ v_c = 2\pi \sqrt{A^2 R_{Q0}^2 + A f n_0 R_0 \cos[2\pi f (t - n_0)]} + A f n_0 R_0 \cos[2\pi f (t + n_0)] \] (22)

\[ F_{nc} = K_1 \frac{v_w}{v_c} \delta_s \] (23)

When only chip formation is considered, the ratio (A1) of the normal and tangential component forces of a single polishing particle is determined by the shape of the polishing particle [23].

\[ F_{tc} = A_1 K_1 \frac{v_w}{v_c} \delta_s = K_2 \frac{v_w}{v_c} \delta_s \] (24)

where \( K_1, K_2 \) is the chip formation force constant, which is confirmed by experimentation.

2) FRICTION FORCE COMPONENTS

Due to the area of the chip cross-section during the VARP process is smaller than the area where the tip of the polishing particle slides along the workpiece, the friction force component needs to be calculated during the polishing force calculation. And the friction component will change with the wear of the polishing pad [23].

\[ F_{nf}' = \delta \bar{p} \] (25)

\[ F_{tf}' = \mu F_{nf}' = \mu \delta \bar{p} \] (26)

where \( \delta \) is the tip area of the polishing particle, \( \mu \) is the friction factor, and \( \bar{p} \) is the average pressure at the pad-workpiece interface.

The complete normal and tangential components of friction are written as

\[ F_{nf} = N_t \delta \bar{p} \] (27)

\[ F_{tf} = \mu N_t \delta \bar{p} \] (28)

Assuming the polishing path as a parabolic function, the difference value (\( D \)) between the radius of the polishing roller (\( R_0 \)) and the curvature radius (\( R \)) of the theoretical polishing path [31]

\[ \Delta = \frac{1}{R_0} - \frac{1}{R} \] (29)

\[ \Delta = \pm \frac{4V_w}{V_c d_e} \] (30)

According to Zhang’s research [31], the average pressure (\( \bar{p} \)) of the workpiece-polishing pad interface and deviation (\( \Delta \)) can be regarded as linear correlation, and the relationship can be written.

\[ \bar{p} = P \Delta = \frac{4P V_w}{V_c d_e} \] (31)

where \( P \) is the average pressure coefficient.

There may be elastic, elastoplastic, and plastic contact during processing. Therefore, the coefficient of friction will vary with process parameters and average pressure. The variable friction coefficient can be calculated via the friction binomial law [32]

\[ \mu = \frac{\alpha_0 A_0}{W} + \beta = \alpha_0 \bar{p} + \beta \] (32)

where \( \alpha_0, \beta \) are dimensionless factors, which are rest with the performance of the workpiece and the polishing pad and the mechanical and physical performance of the contact interface.
Introducing (30), (31), and (32) in (27) and (28), respectively. The entire tangential and normal frictional force components are derived as

\[
F_{nf} = N_a \delta \bar{p} = N_a \left[ 4 \delta PV_w \over V_c d_e \right] = N_a \left[ 4K_3 V_w \over V_c d_e \right] \tag{33}
\]

\[
F_{tf} = \mu N_a \delta \bar{p} = \left[ 4 \delta PV_w \over V_c d_e \right]^2 + \left[ 4 \delta PV_w \over V_c d_e \right] \tag{34}
\]

where \( K_3, K_4, \) and \( K_5 \) are component coefficients of friction, which are obtained from the experiment.

3) PLOUGHING FORCE COMPONENTS

In VARP processing, the plough is another material removal mechanism. The plough energy comes from the deformation and flow of the material. Including the flow phenomenon of the material from the processing track to both sides in the VARP process, and the plastic distortion of the workpiece material passing through the lower side of the abrasive grain in the processing track. Generally speaking, the plough action occurs in the material flow stage without cutting, the transition stage, and the cutting stage when cutting occurs [31]. However, to simplify the calculation, this article only considers the cutting stage with a larger duration.

According to the research of Vathaire et al. [33], a plough force model can be established. The cross-sectional area \( Q_s \) of the chip is the area of action of the plough. The ploughing force can be given as:

\[
F'_p = H_v Q_s \tag{35}
\]

\[
Q_s = R^2 \arccos \left( 1 - \frac{\delta_s}{R} \right) - (R - \delta_s) \sqrt{R^2 - (R - \delta_s)^2} \tag{36}
\]

\[
F_{np} = N_a H_v \left[ R^2 \arccos \left( 1 - \frac{\delta_s}{R} \right) - (R - \delta_s) \sqrt{R^2 - (R - \delta_s)^2} \right] \tag{37}
\]

\[
F_{tp} = K_6 N_a H_s \left[ R^2 \arccos \left( 1 - \frac{\delta_s}{R} \right) - (R - \delta_s) \sqrt{R^2 - (R - \delta_s)^2} \right] \tag{38}
\]

where \( K_6 \) is the dimensionless coefficient of the tangential plough force component, which is obtained from the experiment. \( H_v \) is the Vickers hardness, \( H_s \) is the scratch hardness.

4) ENTIRE POLISHING FORCE

Introducing (23), (33), and (37) into (17), and introducing (24), (34), and (38) into (18). The entire equations of normal and tangential polishing force are derived as

\[
F_n = F_{nc} + F_{np} + F_{nf} = K_1 \frac{V_w}{V_c} \delta_s + N_a \left[ \frac{4K_3 V_w}{V_c d_e} \right] + N_a H_s \left[ R^2 \arccos \left( 1 - \frac{\delta_s}{R} \right) - (R - \delta_s) \sqrt{R^2 - (R - \delta_s)^2} \right] \tag{39}
\]

\[
F_t = F_{tc} + F_{tp} + F_{tf} = K_2 \frac{V_w}{V_c} \delta_s + \left( \frac{4K_4 N_a V_w}{V_c d_e} \right)^2 + \left( \frac{4K_5 N_a V_w}{V_c d_e} \right) + K_6 N_a H_s \left[ R^2 \arccos \left( 1 - \frac{\delta_s}{R} \right) - (R - \delta_s) \sqrt{R^2 - (R - \delta_s)^2} \right] \tag{40}
\]

V. VARP EXPERIMENTS

A. EXPERIMENTAL SET-UP

As shown in the Fig. 19, the experiments were launched on the roller-type polishing machine. In this article, the pressureless SiC is selected as the workpiece, and the workpiece size is 10mm × 10mm × 5mm. Besides, the plane processing trajectory of the carried SiC workpiece was produced by the DN-VPD which was driven by orthogonal PZTs simultaneously. A signal generator (DG4162, Rigol) and a power amplifier are adopted to produce and magnify the input control signals, respectively. During the polishing experiments, the open-loop experiment was adopted to polish the workpiece carried by 3D printing baseplate. Meanwhile, the dynamic force data were measured using a 3-dimensional dynamometer (Kistler 9257B). The force signal obtained by the measurement is magnified by a charge amplifier (Kistler 5070A) and gathered by a data acquisition card (Kistler 2855A4). Finally, the output signal is displayed on the PC.

![FIGURE 19. Experimental equipment for processing experiments.](image-url)

B. DETERMINATION OF EXPERIMENTAL COEFFICIENTS

By solving the linear equation, the other six coefficients \( K_1, K_2, K_3, K_4, K_5, \) and \( K_6 \) were confirmed from the five sets of polishing experimental. To make the model more accurate, a 4-factor 3-level orthogonal experiment was performed with factors such as rotational speed, feed speed, amplitude, and frequency, as shown in Table. 3. The normal polishing force and the tangential polishing force were gathered using a dynamometer, and the initial pressure value was subtracted. Table. 4 shows the parameters used for polishing force modeling of the VARP process.

The diamond particles with a diameter of 1 μm are selected in the orthogonal experiment. The downforce of the polishing pad is subtracted from the measured data, and the model is subjected to regression analysis to determine the
experimental coefficient in the model. The experimental coefficients of the tangential component and the normal component of the polishing force on the VARP are shown in Table 5.

\[
F_n = 1.218914 \times 10^3 \frac{V_w}{V_c} \delta_s + N_a \left[ -0.261108 \frac{V_w}{V_c d_e} \right] \\
+ N_a H_s \left[ R^2 \arccos \left( 1 - \frac{\delta_s}{R} \right) \right] \\
- (R - \delta_s) \sqrt{R^2 - (R - \delta_s)^2} \\
(41)
\]

\[
F_t = 3.305726 \times 10^3 \frac{V_w}{V_c} \delta_s \\
+ \left( \frac{0.311456 N_a V_w}{V_c d_e} \right)^2 + \left( \frac{0.33324 N_a V_w}{V_c d_e} \right)^2 \\
+ 6.373310 N_a H_s \left[ R^2 \arccos \left( 1 - \frac{\delta_s}{R} \right) \right] \\
- (R - \delta_s) \sqrt{R^2 - (R - \delta_s)^2} \\
(42)
\]

**TABLE 4. Material properties for mathematical modeling of VARP process.**

| Parameter | Value     | Unit |
|-----------|-----------|------|
| D         | $1 \times 10^{-3}$ | mm   |
| d         | 46        | mm   |
| b         | 5         | mm   |
| $R_0$     | 23        | mm   |
| $E_r$     | 90        | Mpa  |
| $v_r$     | 0.5       | -    |
| $E_e$     | $4.2 \times 10^5$ | Mpa  |
| $v_e$     | 0.14      | -    |
| $E_s$     | $1.14 \times 10^6$ | Mpa  |
| $v_s$     | 0.07      | -    |
| $\chi$    | 0.03      | -    |
| $H_s$     | $4.2 \times 10^4$ | Mpa  |
| $\beta$   | $3 \times 10^{-2}$ | mm   |
| $\sigma_t$ | $2.2 \times 10^{-2}$ | mm   |

**C. FORCE MODEL VERIFICATION**

To verify the feasibility of the theoretical model, quantitative processing experiments were performed on the SiC workpieces based on polishing parameters, such as output amplitude, output frequency of the DN-VPD, rotational speed, and feed speed. To obtain the uniformity of the concentration of the polishing slurry, a mixer, and a high-speed homogenizer are used to prepare the slurry. In addition, a diamond slurry with a particle size of 1 µm was selected for 16 polishing experiments. The online test data was recorded with a data acquisition card, and the average normal force and average tangential force with a period of 1 s were selected.

The results show that the input variables $v_f$, $n_0$, and the vibration parameters of DN-VPD affect the polishing force obtained using (41) and (42) for prediction and testing, as shown in Fig. 20 and 21. The maximum error between the results predicted by the VARP force model and the measured normal force and tangential force is about 7.7%. Obviously, the change trend and quantitative value of the results predicted by the VARP force model are in good agreement with the measured normal force and tangential force. In the VARP process, the normal force increases with the increase of $v_f$, and the increase rate of the normal force decreases with the increase of $n_0$. The normal force decreases with the increase of $n_0$, $A$, and $f$, and the rate of normal force decrease decreases with the increase of $n_0$ and $f$, as shown in Fig. 20. In the VARP process, the tangential force increases with the increase of $v_f$, and the increase rate of the tangential force increases with the increase of $v_f$. The tangential force decreases with increase of $n_0$, $A$ and $f$, as shown in Fig. 21. Therefore, the normal force and tangential force of the VARP process can be controlled microscopically by adjusting $A$ and $f$ of the DN-VPD.

**D. RESULTS AND DISCUSSION**

Subsequently, to verify the impact of the vibration parameters on the roller polishing, a comparative experiment of the VARP and roll polishing was carried out. The experimental results were examined by a laser interferometer, as shown in Fig. 22.

In this section, the white light interferometer (ZygoNewview, USA) is used to detect the polished surface roughness and topography of the workpiece. The surface roughness $Sz$ and $Sa$ were chosen to evaluate the surface quality, which indicates peak-to-valley value and surface height deviation, respectively. The original surface profile of the workpiece has a large number of randomly distributed protrusions, causing the surface quality poor, as shown in Fig. 22(a). Compare to the 1085 nm $Sa$ and 10.237 µm $Sz$ of the original workpiece. The surface quality was significantly improved after conventional roll-type polishing, as shown in Fig. 22(b). Meanwhile, the $Sa$ and $Sz$ values achieved 168 nm and 6.415 µm, respectively. However, the surface of the workpiece still existed trenches and more burrs.
After the DN-VPD is applied to roll-type polishing, the number of grooves and burrs on the surface of the SiC workpiece is greatly reduced, and the surface of the workpiece becomes significantly smoother. In addition, the $S_a$ and $S_z$ values of the polished SiC workpiece are reduced to 45 nm and 5.324 µm, respectively, as shown in Fig. 22(c). The results show that the introduction of DN-VPD in roll polishing can effectively improve the processing effect.

To investigate the effect of frequency and amplitude of the DN-VPD on the surface quality during VARP, the experiments considering vibrational parameters were performed, and the results are shown in Fig. 23. Compared with Fig. 22(b), when the amplitude and frequency were 9 µm and 100 Hz, respectively, the phenomenon of surface burrs and processing marks was improved, as shown in Fig. 23(a). The $S_a$ value was 132 nm, and the $S_z$ value was 3.440 µm. After the polishing amplitude and frequency were increased to 18 µm and 300 Hz, respectively, the burr and ditch phenomenon on the processed surface was further reduced, as shown in Fig. 23(b) and (e). In the polishing process, the polishing particles are subjected to the vibration of the platform to reduce the polishing force and increase the area processed in a unit time. When the amplitude and frequency were increased to 27 µm and 500 Hz, respectively, the surface was flatter, and the processing marks were further reduced, as shown in Fig. 23(c) and (f).

Fig. 24 shows the SEM images of the original and polished workpiece surface. As shown in Fig. 24(a), a large number of

| $K_1$  | $K_2$  | $K_3$  | $K_4$  | $K_5$  | $K_6$  |
|--------|--------|--------|--------|--------|--------|
| 1.218914×10^6 | 3.305726×10^7 | -0.261108 | 0.077864 | 0.083310 | 6.373310 |

**TABLE 5.** Material properties for mathematical modeling of VARP process experimental coefficients of tangential and normal forces.

**FIGURE 20.** Normal polishing force under different machining parameters.

**FIGURE 21.** Tangential polishing force under different machining parameters.

**FIGURE 22.** Surface topography: (a) original, (b) Non-vibration polishing ($v_f = 0.2$, $n = 5 \text{ rad/s}$, $A = 0 \mu m$, $f = 0 \text{Hz}$) and (c) Vibration polishing ($v_f = 0.2$, $n = 5 \text{ rad/s}$, $A = 24 \mu m$, $f = 400 \text{Hz}$).
FIGURE 23. Surface morphology of multiple vibration parameter experiments.

FIGURE 24. SEM micrograph: (a) original appearance, (b) Non-vibration polishing ($v_f = 0.2 \text{mm/s}$, $n = 3 \text{rad/s}$, $A = 0.1 \text{mm}$, $f = 0 \text{Hz}$), (c) Vibration polishing ($v_f = 0.2 \text{mm/s}$, $n = 3 \text{rad/s}$, $A = 12 \text{μm}$, $f = 600 \text{Hz}$) and (d) Vibration polishing ($v_f = 0.2 \text{mm/s}$, $n = 3 \text{rad/s}$, $A = 36 \text{μm}$, $f = 300 \text{Hz}$).

Under the vibration parameters of frequency (600 Hz) and amplitude (12 μm), the surface damage of the workpiece is obviously improved. When the vibration frequency is 300 Hz and the vibration amplitude is 36 μm, the polished workpiece is smoother. The experimental results show that after applying DN-VPD to roll-type polishing, the machining marks and damage on the surface of the workpiece are obviously improved. And it is found that the increase of the amplitude and frequency of DN-VPD can improve the processing effect.

VI. CONCLUSION

In this article, a DN-VPD is developed for VARP of SiC ceramics, and the performance of the DN-VPD is verified through finite element simulation and prototype testing. A prediction model of the VARP force was established to predict and guide the polishing experiments. Finally, polishing experiments were performed to verify the effectiveness of the DN-VPD and the VARP force model. The main conclusions of this article can be summarized below:

1) The DN-VPD was driven by a couple of the PZTs to generate the plane processing trajectory. The results of the prototype testing and the finite element simulation showed that the DN-VPD possessed a working space of $38 \text{μm} \times 42 \text{μm}$, the inherent frequency of 1198 Hz, and the crosstalk in the x and y directions is 1.6% and 1.4%, respectively.

2) The polishing force was modeled by incorporating the motion track of a single abrasive and the contact characteristics of the polishing pad and workpiece. The results of theoretical models showed that the VARP force raises with the increasing of rotation speed $n$, whereas decrease with the increase of feed speed $v_f$, amplitude $A$, and frequency $f$. Comparing the predicted VARP forces with the experimental values, the results showed that the predicted values were in keeping with the experimental values.

3) The results of the polishing experiment show that the use of DN-VPD in roll-type polishing can improve the surface quality of the workpiece. When the amplitude increases from 9 μm to 36 μm, the $S_a$ value decreases from 132 nm to 54 nm, and the $S_z$ value decreases from 3.440 μm to 0.724 μm. When the frequency increases from 100 Hz to 700 Hz, the $S_a$ value decreases from 132 nm to 47 nm, and the $S_z$ value decreases from 3.44 μm to 0.864 μm.

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