Research Article

Experimental Optimization of Annular Polishing Parameters for Silicon Carbide

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Machined surface quality has a strong impact on the functionality of silicon carbide-based components and devices. In the present work, we first analytically investigate the complex coupling of motions in annular polishing based on the Preston equation, which derives the influential parameters for material removal. Subsequently, we conduct systematic annular polishing experiments of reaction-bonded silicon carbide to investigate the influence of derived parameters on polished surface quality, which yield optimized polishing parameters for achieving ultralow surface roughness of reaction-bonded silicon carbide.

1. Introduction

Reaction-bonded (RB) silicon carbide (SiC) is one of the preferred materials for manufacturing optical mirrors due to its unique characteristics of low density, high strength, low thermal expansion, high thermal conductivity, and high chemical inertness [1]. Machined surface quality plays an important role in determining the functionality of SiC-based components and devices. For instance, according to the theory of total integral scattering (TIS), the surface scattering capability of optical mirror is closely related to its surface roughness, as the TIS increases sharply with the increase of surface roughness. The high surface scattering coefficient will cause the system to produce stray light, which decreases the reflectivity of SiC mirrors and consequently results in the degradation of imaging quality of optical system [2]. Thus, improving machined surface quality of SiC is critical for facilitating the performance of SiC mirrors.

At present, annular polishing technology is an efficient method to obtain SiC mirrors with high surface quality [3–6]. Some typical work are as follows: Rupp et al. studied the grinding and polishing of conventional optics and found

that the contact pressure between the specimen and the polishing pad changes dynamically, and is a function of time and location of points on the specimen [2]. Aspden et al. developed a CNC surface polisher that uses a small tool to achieve the desired profile by convolution to calculate the dwell time of the widget. In their topics, there is no single mathematical model that completely correlates the mechanical motion of optical surfaces with the amount of material removed during grinding or polishing process [7]. Wagner and Shannon established a model to describe the relationship between the mechanical motion and the change in surface area and to calculate the material removal of the specimen surface through the mathematical method and optical kinematics principle [8]. Gao and Cao studied the relationship between motion parameters, grinding mechanism, and the trajectory of the specimen [9]. Shen and Yuan studied the influence of applied load on pressure profile in the polishing process [10]. Liu et al. introduced the use of annular polishing technology for the manufacturing of large-diameter square optical components [11]. On the other side, the annular polishing is strongly dependent on polishing conditions. Wang et al. found that as the pressure

increases, the contact area between the polishing pad and the workpiece increases, while the mechanical friction is enhanced and the material removal rate is high. As the rotation speed increases, the thickness of the polishing liquid film between the polishing pad and the workpiece gradually increases, the flow rate of the polishing liquid increases, leading to increased materials taken away from the processed surface under an increased material removal rate [12]. Sun et al. found that the oxidant, the complex agent content, and the polishing solution PH value in the polishing solution have a great influence on the material removal rate [13]. Hu et al. studied the effects of abrasive types such as SiO_2 , Al_2O_3 , and CeO , the concentration of abrasives and the size of abrasive grains on the polishing effect [14]. More recently, Zhang et al. performed finite element simulations and experiments of annular polishing of SiC and found that the distribution of contact pressure on the SiC specimen is significantly affected by the polishing speed, Poisson's ratio, and the elastic modulus of polishing pad [15].

Previous studies have obtained many valuable insights. However, most of previous work is mainly utilizing a sole method, either experiment or simulation. In particular, the lack of systematic experimental demonstration of theoretical analysis greatly restricts the deep understanding of the annular polishing mechanism of SiC. Therefore, based on the Preston equation and motion simulation, this paper analyzes the law of motion coupling in annular polishing and summarizes the polishing parameters that affect the annular polishing. Based on the analytical theoretical investigations, annular polishing experiments are carried out to further study the influence of different polishing parameters and ultimately obtain the optimized polishing parameters. This research has important theoretical significance and practical value to guide the annular polishing processing of SiC.

2. Analytical Investigation of Annular Polishing

2.1. Kinematic Coupling of Motions. Figure 1(a) illustrates a typical annular polisher, which mainly consists of a polishing disc, a carrier disc, and a swinging bracket, respectively. The specimen is pasted on the carrier disc with paraffin, which means that the specimen has a synchronous speed with the carrier disc. The applied pressure is provided by the weight of carrier disc. Accordingly, Figure 1(b) illustrates the simplified motion diagram in the annular polishing, which indicates that the kinematic coupling of relative motions mainly includes the rotation of polishing disc and the rotation of carrier disc. As indicated in Figure 1(b), the speed of carrier disc is ω and the speed of polishing disc is δ . The distance from the center of specimen O_2 to a point A on the carrier disc is r , and the distance from the center of polishing disc O_1 to the center of the carrier disc O_2 is R . The angle between the line segments AO_2 and O_1O_2 is θ . The speed at the point A on the polishing disc relative to O_1 is V_1 , and the speed at the point A on the specimen relative to O_2 is V_2 , so the relative speed of the specimen and the polishing disc at point A is V , which can be derived from the following equation [16].

$$V(r, \theta) = [R^2\delta^2 + r^2(\delta - \omega)^2 + 2rR\delta(\delta - \omega)\cos\theta]^{1/2}. \quad (1)$$

2.2. Preston Equation. Both material removal rate and surface quality of specimen in the annular polishing process are strongly affected by processing polishing parameters, which have complex interactions. Preston et al. simplified the Preston equation [17] to characterize the relationship between material removal and polishing speed V , applied pressure P , and other external factors, as shown in the following equation [17]:

$$\frac{dh}{dt} = kPV = kP\frac{ds}{dt}, \quad (2)$$

where h is the amount of material removal and k is a proportional constant that is related to various environmental factors. Therefore, the amount of material removal at one specific point can be derived according to Equation (2). However, the contact between specimen and polishing disc changes dynamically with polishing time, which induces uncertainties in the analytical investigation of annular polishing process. Therefore, three main assumptions are made to simplify the operation: (1) specimen and polishing disc are fully contacted without separation; (2) the applied pressure does not change with polishing time; and (3) the proportional constant k does not change with polishing time. According to the Preston equation, the amount of material removal within a specific polishing time can be derived by integrating over time t , as shown in the following equation:

$$h(r) = k \int_0^T P(r, t) \cdot V(r, t) dt. \quad (3)$$

It can be seen from Equation (3) that the material removal is only dependent on the resultant speed V , given the k and the P are constant values. By substituting the relative velocity derived from Equation (1) into Equation (3), the material removal at point A can be derived, as shown in the following equation [15]:

$$h(r) = k \int_0^T P(r, t) \cdot [R^2\delta^2 + r^2(\delta - \omega)^2 + 2rR\delta(\delta - \omega)\cos\theta]^{1/2} dt. \quad (4)$$

The amount of material removal at any point on the specimen can be calculated from Equation (4). The pressure P is affected by the type of polishing pad and polishing solution. Based on the annular polishing motion simulation and the Preston equation, four influential parameters can be determined: as polishing solution, polishing pad, polishing time, and rotation speed of polishing disc, respectively.

3. Annular Polishing Experiment of RB-SiC

3.1. Effect of Polishing Solution Material. It has been demonstrated that polishing solution's particle size, particle hardness, and concentration have a strong impact on the

FIGURE 1: Illustration of annular polishing. (a) Model of annular polisher; (b) motion analysis of annular polishing. Reproduced from Zhang et al. [15] (under the Creative Commons Attribution License/public domain).

polishing process [18]. We first investigate the influence of polishing solution material on the polishing results. Three kinds of polishing solution materials such as alumina, silica, and diamond are considered. For each polishing solution material, the average particle size is the same as 250 nm. In the polishing experiments, the polyurethane polishing pad is used with a rotation speed of 120 r/min. The polishing time is 60 min. After polishing, the surface roughness of the specimen is measured by a Taylor Hobson surface profiler.

Figure 2 presents the value of surface roughness for each polishing solution material. The surface roughness is the maximum of 7.3 nm for the alumina, followed by 6.1 nm for the silica, and the minimum of 3.2 nm for the diamond. It can be seen from Figure 2 that with the increase of abrasive hardness of the polishing solution, the surface roughness of the specimen decreases gradually, as the increase of abrasive hardness results in an improvement not only in the mechanical force between the specimen and abrasive but also in the quality of the specimen surface.

FIGURE 2: The relationship between the surface roughness and the type of polishing solution.

3.2. Effect of Polishing Pad Material. The polishing pad should have the following conditions: appropriate rigidity and hardness, a certain elasticity, good retention of the polishing solution, excluding the by-product of polishing process, and low impurities of the polishing pad [19]. In this paper, we use four kinds of polishing pad materials: the cot polishing pad, the matte leather polishing pad, the synthetic leather polishing pad, and the polyurethane polishing pad.

In different polishing experiments with different polishing pad materials, all the polishing parameters are kept constant. And the diamond suspension solution is used as the polishing solution for each experiment. The speed of polishing plate is 120 r/min, and the polishing time is 60 min. After the polishing experiment, the measured surface roughness of SiC is 7.6 nm, 6.9 nm, 8.1 nm, and 2.8 nm for the cot polishing pad, the matte leather polishing pad, the synthetic leather polishing pad, and the polyurethane polishing pad, respectively, as shown in Figure 3.

It can be seen from Figure 3 that surface roughness drops to the smallest value when using the polyurethane polishing pad. It can be concluded that due to the higher hardness of SiC specimen than the cot polishing pad, abrasive particles are pressed into the polishing pad, and thus are unable to produce effective force on the SiC surface, resulting in low processing precision and high surface roughness. The hardness of matte leather and synthetic leather polishing pad is higher, but the surface is easier to be scratched as a result of the higher interaction force, which results in higher surface roughness. The hardness of polyurethane polishing pad is moderate, which can obtain the best polishing effect with the lowest surface roughness of 2.8 nm.

3.3. Effect of Polishing Time. We further investigate the influence of polishing time on the machined surface quality of SiC. While maintaining the other polishing parameters

FIGURE 3: The relationship between the surface roughness and the type of polishing pad.

unchanged, only the polishing time is changed. The polishing time is divided into six groups: 30 min, 60 min, 90 min, 120 min, 150 min, and 180 min, respectively. In each experiment, the diamond suspension is used as the polishing solution, and the polyurethane polishing pad is utilized. The polishing pad speed is 120 r/min. After the polishing, the measured surface roughness is 3.2 nm, 2.5 nm, 2.1 nm, 1.6 nm, 0.8 nm, and 1.2 nm for the polishing time of 30 min, 60 min, 90 min, 120 min, 150 min, and 180 min, respectively, as shown in Figure 4.

It can be seen from Figure 4 that the surface roughness changes with the polishing time: it first decreases steadily and then starts to increase from the polishing time of 150 min, indicating a critical polishing time of 150 min. In the initial stage of the polishing experiment, large abrasive particles are embedded into the surface to accommodate large pressure, which leads to generation of surface scratches, thus affecting the surface quality. With the increase of polishing time, abrasive particles break up to small particles with sharp edges that have good cutting performance, which facilitates the formation of smooth surface of the specimen. The surface roughness reaches the lowest value of 0.8 nm at the polishing time of 150 minutes. However, with the further increase of polishing time, the increase of surface temperature produces thermal stress, which affects the machining accuracy and lowers the surface roughness.

3.4. Effect of Rotation Speed of Polishing Disc. We also investigate the influence of rotation speed of polishing disc. Six rotation speeds of polishing disc are considered: 50 r/min, 70 r/min, 90 r/min, 120 r/min, 140 r/min, and 160 r/min, respectively. For each rotation speed, all the other polishing parameters are the same. The diamond suspension is used as the polishing solution, and the polyurethane polishing pad is utilized. The polishing time is 60 min. After the polishing experiment, the measured surface roughness is

FIGURE 4: The relationship between the surface roughness and the polishing time.

3.3 nm, 2.7 nm, 2.5 nm, 1.6 nm, 1.2 nm, and 2.6 nm for the rotation speed of 50 r/min, 70 r/min, 90 r/min, 120 r/min, 140 r/min, and 160 r/min, respectively, as shown in Figure 5.

It can be seen from Figure 5 that with increasing rotation speed, the surface roughness first decreases and reaches the lowest value of 1.2 nm at the rotation speed of 140 r/min and then increases with a further increase of rotation speed. It is known that a high rotation speed of the polishing disk can increase the efficiency of the polishing process. However, the higher the rotation speed of polishing disc, the lower the processing stability, which result in the lower surface formation accuracy.

Based on the above analysis, the optimized parameters of annular polishing of SiC are summarized as follows: a rotating speed of polishing disc is 140 r/min, a polishing time is 150 min, using the polyurethane polishing pad and the diamond suspension solution. Under the optimized polishing conditions, a high-quality SiC specimen with a surface roughness of 1.31 nm is obtained. Figure 6 shows the characterized SiC specimen before and after polishing, indicating polished SiC with good surface quality can be obtained by using the optimized annular polishing parameters.

4. Summary

In this work, we experimentally investigate the optimization of annular polishing parameters of RB-SiC by first analytical investigation of influential parameters based on the Preston equation and the coupling of polishing motions, and then systematic polishing experiments and characterization. It is found that the annular polishing process can be greatly influenced by the polishing solution: the polishing pad material, the polishing time, and the rotation speed of polishing disc. The optimized annular polishing parameters are a rotating speed of polishing disc of 140 r/min, a polishing time of 150 min, using polyurethane polishing pad

FIGURE 5: The relationship between the surface roughness and the rotation speed.

FIGURE 6: Morphology and microstructure of polished SiC. (a) Before polishing, (b) after polishing, (c) surface morphology before polishing, (d) surface morphology after polishing, (e) surface microstructure before polishing, and (f) surface microstructure after polishing.

and diamond suspension solution, which lead to a surface roughness of 1.31 nm of RB-SiC by annular polishing.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Y. L., H. L., and J. Z. conceived and designed the experiments; L. H. and Y. S. performed the analytical investigation and experiments; Y. L. and J. Z. analyzed the data and wrote the paper.

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