Study on removal characteristic of silicon carbide surface in precision mechanical polishing

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Abstract: Precision mechanical polishing was one of the primary techniques for the fabrication of optical components with both high-precision and high-quality surfaces. However, few studies have been reported on the removal rate characteristics of silicon carbides (SiC) in high finish quality polishing processes. SiC was an important ceramic material for many critical industrial and aerospace applications. A theoretical investigation and a series of polishing experiments in computer controlled precision polishing process were presented. And a better understanding of removal mechanisms of SiC surfaces was also proposed for optimizing surface quality. Head speed, tool pressure, tool offset and polishing angle were selected to analyze the surface removal tendency. The Taguchi method was used as an efficient method to optimize the polishing conditions and reduce excessive experimental requiring. Moreover, the results imply the polishing parameters combinations required to achieve the desired surface finish and better application of removal characteristic.

Key words: precision polishing; surface quality; removal characteristic; silicon carbide

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精密数控抛光碳化硅表面去除特性研究

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摘　要: 计算机数控精密机械抛光技术是制造高精度、高质量光学元件表面的主要技术之一。然而,对于碳化硅材料表面去除特性方面的研究却相对较少。在航天航空领域中,陶瓷类材料碳化硅的应用较为广泛。针对计算机数控精密机械抛光技术,根据一系列的抛光实验,研究并总结出碳化硅材料表面的去除机理。基于选择不同等级的四种变量参数:抛光磨头转速、抛光压力、磨头补偿量和抛光头

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角度,分析碳化硅材料表面的去除趋势。采用 Taguchi 方法可以有效优化实验设计参数、减少实验整体次数。结果表明:文中总结出对应的抛光参数组合和材料表面的去除特性,确保加工出高质量表面的碳化硅材料。

关键词: 精密抛光; 表面质量; 去除特性; 碳化硅

0 Introduction

Surface quality requirements of reflectors in optical systems have becomes more stringent for critical applications in the aerospace industry. In parallel with this the use of ceramics in reflective optical systems has become more common. They have replaced the traditional optical materials such as glasses and metals in spacecraft, space-based telescopes and so on. The material selected in this study is silicon carbide (SiC) which has been attracted increasing interest as the most popular multiphase ceramic material because of its excellent properties such as extremely high hardness, structural stability and low specific density and the exceptional thermal stability. SiC has superior mechanical and thermal properties and high thermal stability which is one of the most important parameters in aerospace optical systems [1]. However its light weight makes it a very suitable material for application in the space environment.

There are four factors (head speed, tool pressure, tool offset and angle) which affect the polishing process. Each factor has different influence in the removal mechanism. The research analyzes the removal tendency of SiC surfaces during the whole polishing process. Although, much has been published on the surface preparation of ceramic materials to reduce the surface roughness, still more work is needed on the preparation of high quality optical surfaces in precision polishing. To address this shortfall a series of experimental investigations has been undertaken to study the surface removal rate and the surface finish of SiC material in the precision polishing process.

1 Computer controlled polishing process

1.1 Precision mechanical polishing of ceramic materials

A comparison of SiC and traditional optical materials is shown in Tab.1. The thermal stability depends on the thermal conductivity (K) and thermal diffusivity($D=K/\rho C$), C is specific heat of the ceramic for using in space environment and ρ is density. Despite its advantages, SiC is quite a difficult material to be machine and polish to high surface finish.

Tab.1 Comparison of SiC and other traditional materials

Parameter	Density ρ	Young's modulus E	Thermal expansion α	Thermal conductivity K	Thermal gradients K/α
Unites	g/cm^3	GPa	$K^{-1}\cdot 10^{-6}$	$W/m\cdot K^{-1}$	$10^6\cdot W\cdot m^{-1}$
SiC	3.2	364	2.44	172	71
Al	2.70	68	22.5	167	6.9
Be	1.85	287	11.4	216	19
Zerodur	2.53	92	−0.09	1.64	18

Mechanical polishing is one type of abrasive machining that can improve the surface finish. In traditional polishing, many processing variables affect the polishing process. The high precision and accuracy characteristics of computer controlled polishing (CCP) has led recently to it becoming a widely used process for the preparation of high quality surfaces with good form accuracy and low surface roughness[2-3].

In this present study, the experiment process is undertaken by using the IRP200 ultra-precision, seven multi-axis polishing machine from ZeekoTM Ltd [4]. It has seven axes, four linear axes X, Y, Z and D and the other three of rotation axis A, B and C as shown in Fig.1 (a). This study focuses on the precision mechanical polishing process in which the polishing tool is held by a small rotating polishing head with a bonnet of 20 mm radius, Fig.1 (b) and (c) respectively. It is divided into two parts including the polishing bonnet and the polishing cloth[5].

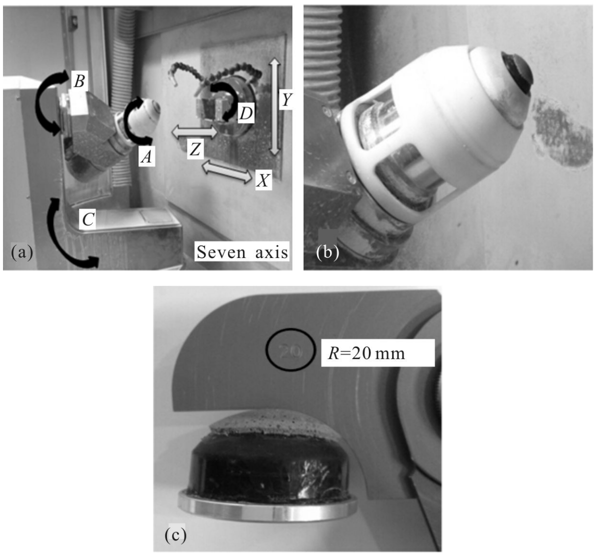


Fig.1 (a) Signed seven axis of precision polishing machine (b) Polishing tool (c) Polishing bonnet and cloth

The multiphase ceramic material of SiC used in this study is provided from Goodfellow Cambridge Limited. The material itself includes both Si and SiC. There are differences in terms of hardness between Si and SiC as Si is much softer. Such ceramic material is hard to be machined by single point diamond turning.

1.2 Preston′s law equation and Gaussian function

According to the Preston′s law[6], the removal rate in contact area between the workpiece and polishing tool is proportional to the pressure and the relative velocity. The removal depth($D_{(A)}$) and material surface removal($M_{(A)}$) at any point in the contact area such as the point A, it could be expressed as

$$D_{(A)}=K\cdot P_{(A)}\cdot V_{(A)} \tag{1}$$

$$M_{(A)}=D_{(A)}\cdot t \tag{2}$$

where K is the constant of Preston′s law; $P_{(A)}$ is the pressure of the point A between the workpiece and polishing tool in the contact area; $V_{(A)}$ is the relative velocity at the point A in the workpiece surface and t is experiment dwell time. The relative velocity in the area is different at any point. It could be obtained that the larger polishing angle, the bigger surface contact area.

Moreover, the removal characteristic is also considered as a removal function and an influence function. As the previous study confirmed [7], the distribution of pressure in the contact area is well approximated by a Gaussian function so that the trend curve of removal characteristic is shown in Fig.2, the diameter of contact area is shown on the X-axis and the Y-axle represents the removal height during the whole polishing process. Fig.2 shows a Matlab simulation system of the removal characteristic.

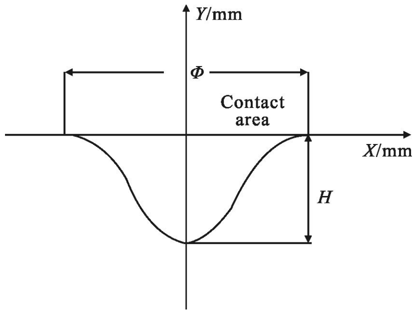


Fig.2 Curve of Gaussian function in contact area

2 Experimental design and setup

2.1 Factors in precision polishing process

The precision mechanical polishing mechanics of the material removal characteristics(MRC) such as the surface roughness and form accuracy were also studied in this work. The polishing geometry of precision polishing is shown in Fig.3. This geometrycan be divided into two parts namely contact surfaceof polishing bonnet and the workpiece. The polishing

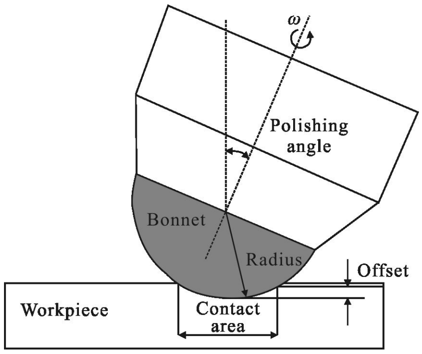


Fig.3 Geometry of precision polishing process

influence factors (PIF) mainly caused by the polishing head, the workpiece and the slurry. All of them combined to impact the MRC in precision polishing process as shown in diagram of Fig.4. The first set of factors consists of polishing head feed and position, process angle, head speed and pressure, bonnet radius and materials, tool offset, etc. The second set includes workpiece radius, form and material, etc. The final set comprises of slurry medium, temperature, concentration and slurry specific gravity. Moreover, the study of these factors could determine the best conditions for correct form and surface quality according to the results of theoretical and experimental.

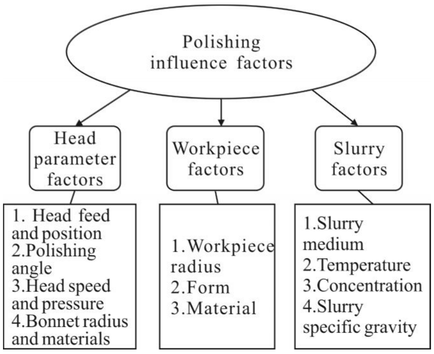


Fig.4 Diagram of polishing influence factors

2.2 Experimental set-up

The experiment focuses on the study of the evaluation of surface removal rate characteristic with different factor parameters. The rough blank of a quadrate SiC flat surface were prepared and used in the experiments reported here. As there are many individual parameters in the polishing process a strategy of varying one at a time would be very time consuming. The Taguchi method is a useful way to optimize and reduce experiment times[8]. It was used in the present study as an efficient method to carry out the experimental study that requires minimal operations on the Zeeko ultra-precision polishing machine[9].

The four factors (*A* to *D*) array was selected to optimize the polishing parameters for the fine surface finish of SiC. Four-nine-leveled factors using Taguchi method and polishing schedule are showed in Tab.2 and Tab.3, the experiments were divided into nine different conditions for independent machining. For all of nine process conditions a dwelling time was fixed at 600 s for each stage in this study. Table 4 shows the polishing experiment parameters, the slurry medium is boron carbide with an average of 35 μm grit size with the concentration of 10% and the bulged polishing bonnet of 20 mm radius. It contacts with the surface of workpiece directly during the experiment process and the polishing slurry is emitted by the tube to the contact surface.

Tab.2 Four factors and three levels for polishing experiment

Levels	Factors			
	A. Head speed /r·min^{-1}	*B*. Tool pressure/bar	*C*. Tool offset/mm	*D*. Angle /(°)
1	800	0.5	0.1	3
2	1 200	1	0.2	6
3	1 600	1.5	0.3	9

Tab.3 Experimental parameters design of Taguchi array L34 (3 level*4 factors)

Conditions	*A*. Head speed /r·min^{-1}	*B*. Tool pressure/bar	*C*. tool offset/mm	*D*. Angle /(°)
1	800	0.5	0.1	3
2	800	1	0.2	6
3	800	1.5	0.3	9
4	1 200	0.5	0.2	9
5	1 200	1	0.3	3
6	1 200	1.5	0.1	6
7	1 600	0.5	0.3	6
8	1 600	1	0.1	9
9	1 600	1.5	0.2	3

Tab.4 Experiment parameters used in present study

Polishing bonnet size	20 mm radius
Polishing slurry material(size)	Boron carbide (average 35 μm)
Dwell time	600 s
Concentration of polishing liquid	10%

The experimental analysis section is divided into two parts: *A* and *B*. In part *A*, a series of polishing experiments were designed and carried out. Measurements of surface profiles before and after these were taken these experiments had a goal of optimizing the polishing strategy to minimize the surface roughness and improve the removal rate[10-11]. They were also designed for analysis by Taguchi methods carried out in Part *B* to study the tendency charts of how the three levels of different parameters influence the surface removal characteristics[12].

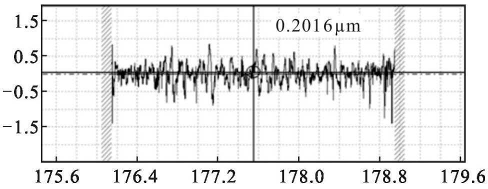
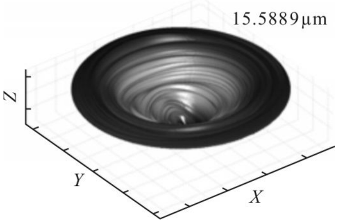
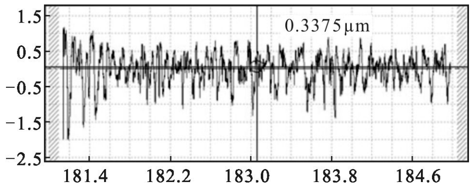
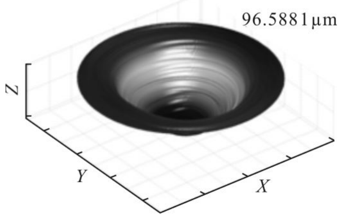
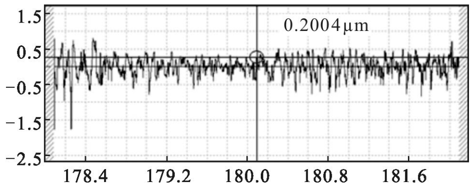
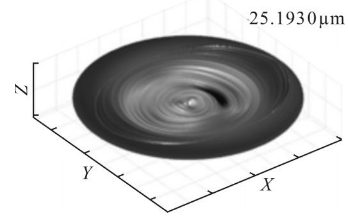
A set of experiments were first designed then executed. The removal function of these nine conditions was measured by a Form Talysurf Seier 2 system. The flat surface before polishing was taken as the base level for comparison with the surface after machining[13-14]. In this way the removal height and the form error map was measured by the Talysurf profilometer. For the coming section, the measurement curve is analyzed step by step, hence, the surface material removal characteristic is predicted.

3 Result and discussion

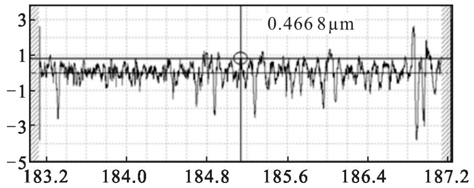
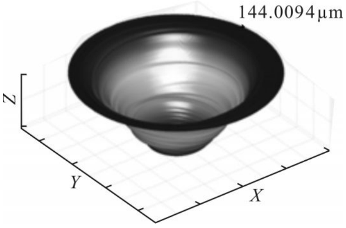
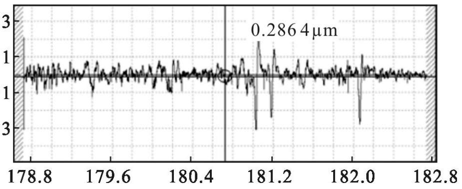
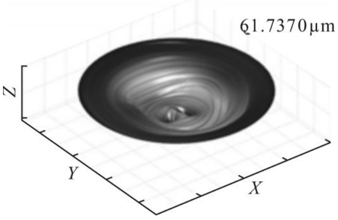
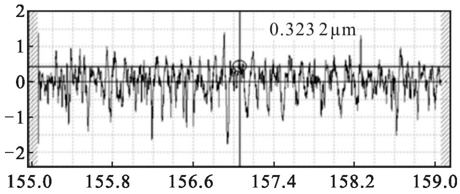
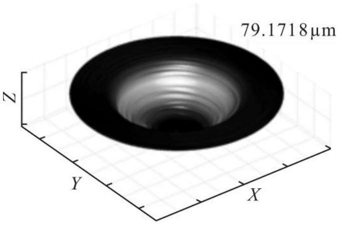
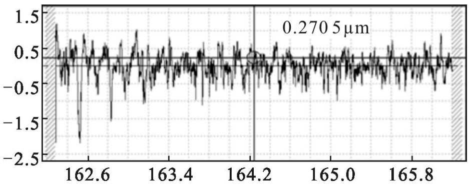
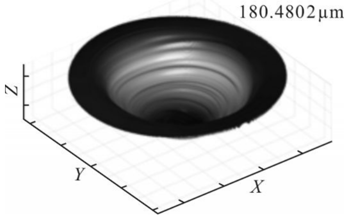
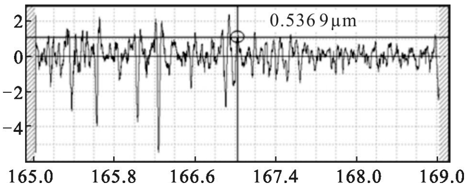
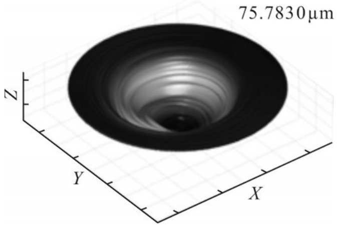
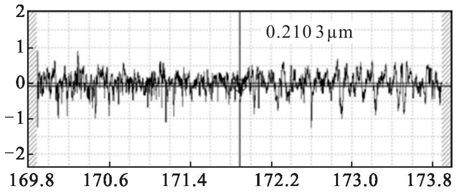
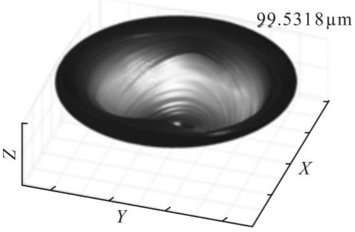
3.1 Optimization combination of process factors on surface removal characteristics

The experimental of Part *A* aimed to optimization combination and feasibility according to the Taguchi method. The measured results of surface roughness analysis with parameter expressed as Ra value of nine samples under different conditions are summarized in Tab.5. It shows the variation of the surface topography and surface roughness profile under nine conditions. By using a fixed dwell time, it could be found that the smallest surface roughness measured by Form Talysurf Series after experiment is given by condition three. For the independent factors, the Taguchi method analysis requires computation of the Signal-to-Noise Ratio (S/N Ratio). The calculated results of these are shown in Tab.6 and the optimum

Tab.5 Actual measured results of 2D and 3D method

Conditions	Roughness results/μm 2D surface roughness profile by Talysurf	Removal maximum height/μm 3D surface topology by Zeeko
1		
2		
3		

Continued Tab.5

Conditions	Roughness results/μm 2D surface roughness profile by Talysurf	Removal maximum height/μm 3D surface topology by Zeeko
4		
5		
6		
7		
8		
9		

combination is summarized in Tab.7 which includes the minimum roughness and the maximum removal rate group.

Tab.6 Analysis result of S/N ratio

	Level	Head speed /r·min^{-1}	Tool pressure/bar	Tool offset/mm	Angle/(°)
For surface roughness	1	12.44	10.63	9.71	12.77
	2	9.10	8.57	9.87	10.20
	3	10.10	12.44	12.06	8.66
For removal rate	1	30.53	37.38	33.14	33.21
	2	38.98	37.70	40.94	40.93
	3	40.89	35.32	36.32	36.26

Tab.7 Optimum S/N ratio condition combination

Biggest S/N ratio	Head speed /r·min^{-1}	Tool pressure /bar	Tool offset /mm	Angle /(°)
For minimum roughness	Level 1	Level 3	Level 3	Level 1
For maximum removal rate	Level 3	Level 2	Level 2	Level 2

3.2 Study of tendency and influence of the removal characteristic

In Part *B* having obtained the before and after surface profiles they could be analyzed to give the tendency and influence of the surface removal characteristic. The surface roughness of nine different conditions before and after experiments were evaluated and compared. In other words, the SiC surface topography pre-experiment is a flat so that the amount of material removal could be consider as the removal height. It is obtained the surface geometry and material removal characteristic of measuring by Talysurf two profiles of at right angles. The 3D surface images could be simulated by Zeeko machine as shown in Tab.5. It needs to be finished by the data such as angle, head speed, offset, pressure and surface feed for different conditions.

Of particular note was that a greater head speed gave a greater surface removal rate and a smaller polishing angle lead to worse surface roughness. As shown in Fig.5 and Fig.6, the results of Taguchi method identified the polishing conditions. The surface finish is strongly impacted by the polishing conditions.

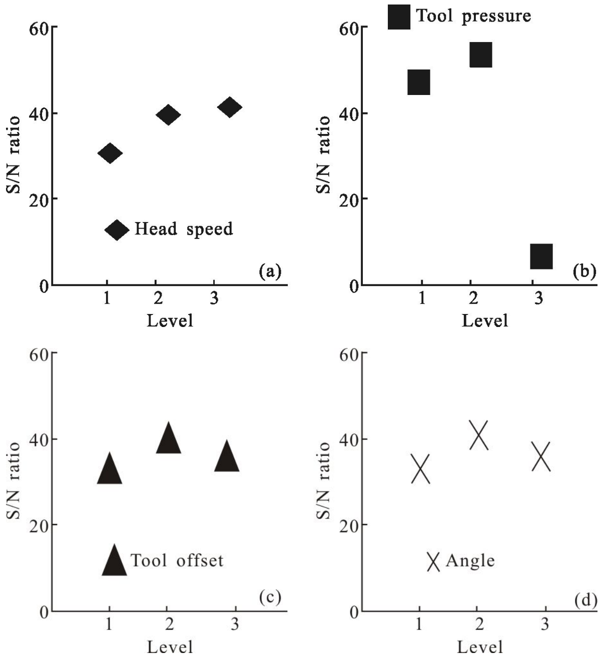


Fig.5 Influence of three level parameters for the removal rate

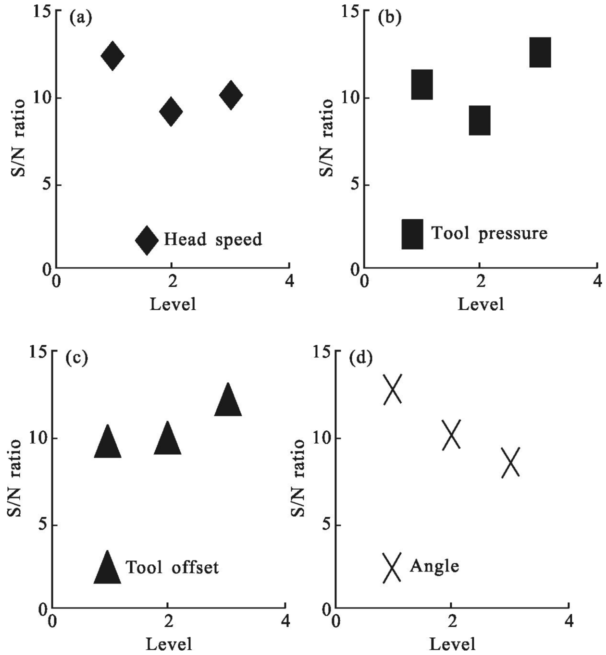


Fig.6 Impact trend of three level parameters for the surface roughness

Actually, it is obvious that the removal rate is not always consistent with different condition of the workpiece surface. According to the previous analysis of Part *A*, the precision polishing process of condition three was found to be effective in decreasing the Ra result, but it was not the best choice for removing surface. In other words, the variation trend of removal rate is not the same as surface roughness. The precision polishing process of condition seven resulted in a maximum removal height. The maximum removal height in each condition is found in the center position of the measurement curve.

4 Conclusions

In this paper, the surface removal rate characteristic is investigated by a precision polishing experimental study. The relationship of factors affecting the surface quality has been determined.

Moreover, the study mainly focused on polishing mechanisms for the ceramic material SiC by a series of experimental studies. Precision polishing has been found to be effective for material removal on the surface of the SiC workpiece. The results provide important ways to get lower surface roughness and better removal characteristics by judicious choice of polishing conditions in the precision polishing process. The Taguchi method analysis was used here to determine how to optimize the conditions and to reduce excessive experimental requiring precision polishing.

From the figures such as Fig.5 and Fig.6, it is obviously to note that the surface finish and removal rate are strongly impacted by the polishing conditions in a non linear fashion. Hence, itproved that the factors value is not the bigger the better for the surface roughness, form control and removal characteristics.

The effects of variations of dwell time on the surface removal characteristic remains to be studied in further research. This study provides important data for optimize the polishing process modeling and expected surface outcome. The present work presents some useful experimental results which could guide the planning of future polishing studies of SiC.

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