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Research Article

The Effect of the Infrared Laser Pre-heating on Ultraviolet Picosecond Laser Polishing of SiC Ceramics

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Abstract

The ultraviolet laser has been used to polish SiC ceramics by its thermal and photochemical effect in previous works to resolve the application limitation of the SiC ceramics for the demand of high-precision applications. In this paper, the "cold polishing" technology of SiC ceramics under photon absorption was studied by using the 355nm ultraviolet picosecond laser, the surface roughness was reduced from Ra=1.616μm to Ra=1.087μm only even though the polishing process parameters has been optimized, because the thermal effect such as gasification was found due to the ablation threshold, and the surface quality of brittle ceramics might be degraded by thermal effect during laser polishing. The ablation threshold of the SiC was obtained as about 0.3J/cm^2. The method of ultraviolet picosecond laser "cold polishing" with infrared laser as preheating source was innovatively proposed to promote the photon-absorption process. By adjusting the preheating process parameters of the infrared laser, the macroscopic morphology and microstructure of polished SiC ceramic surface were analyzed, so as to further clarify the mechanism of photon-absorption effect during the polishing process. It was found that the “cold polishing” by the photon absorption can be promoted owing to the decrease of the ablation threshold under the infrared laser preheating process. Defects such as cracks and porosity cannot be found under the 200× optical microscope, the surface roughness of about 0.66μm can be obtained compared with the 1.087μm by the polishing of ultraviolet picosecond laser. Thus, the ultraviolet picosecond laser polishing with infrared laser preheating technology can be used as the high precise and high efficient polishing technology for the SiC ceramics.

Keywords

SiC Ceramics, Ultraviolet Picosecond Laser, Photon Absorption, Ablation Threshold, Cold Polishing

1. Introduction

Due to the excellent thermal resistance and mechanical properties, silicon carbide ceramic materials are widely used in electronic devices, aerospace, semiconductor industry, and biomedicine [1]. However, due to the poor surface quality of ceramic devices caused by the traditional manufacturing process, the applications of ceramic devices in high precision environment are severely limited. The polishing of ceramic parts has always been the bottleneck of modern manufacturing industry. Chemical, mechanical or electrochemical polishing methods are always adopted in the traditional ceramic polishing process [2, 3], which have a series of problems such as poor machining accuracy, low efficiency, serious pollution, and lack of consistency and stability of product quality. Due to the incompatibility of the requirements of modern manu-

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facturing equipment to achieve high automation, intelligence and network, it is very important to choose or develop a new ceramic polishing process.

In recent years, laser processing technology has developed rapidly, ranging from laser cutting and welding in the field of large-scale processing to fine and deep hole processing and microstructural functional surface manufacturing in the field of micro-processing, the application of laser processing technology has been increasingly extensive [4, 5]. Compared with a variety of traditional polishing processes, laser polishing is a contactless processing method with no pollution, high efficiency, high processing flexibility and consistency, and is a new laser processing application technology [6].

Recently, massive research work has been done on the polishing of metal materials in the domestic and overseas, and high surface quality of the metal piece such can be achieved by laser polishing. Not only the surface roughness and the residual stress and of metal parts could be greatly reduced, but also surface hardness, wear resistance and fatigue strength and of metal parts could be strengthened by the laser polishing process. The laser polishing of metal pieces are mainly divided into continuous-laser polishing and pulsed-laser polishing. The continuous laser is mainly used for rough polishing, while pulsed laser is mainly used for fine polishing [7, 8]. The research on laser polishing of 3D printed parts has been carried out in Beihang Univeristy [9, 10]. Xiao [11] et al. recently conducted a study on laser polishing assisted by steady-state magnetic field, and the roughnesse of the steel piece (Ra=1.87μm) was reduces to Ra=0.18μm by a large scale. Temmler [11, 12] et al. studied the polishing of stainless steel by pulsed laser, and the roughness of the polished surface was reduced by 92%.

Compared with the metal material, few researches on laser polishing of ceramic parts could be found due to the high melting point, high hardness, high viscosity and greater brittleness of ceramic materials [13]. In the process of ceramic polishing based on short pulse laser, the melting, gasification, microcrack and photochemical interaction of ceramic materials could be found. Therefore, it is urgent to study the mechanism of laser polishing ceramics, so as to achieve high precision polishing of ceramic parts. The polishing process for the brittle ceramic parts are mainly divided into thermal polishing and photochemical polishing principle, according to different laser polishing mechanism. For IR laser, the polishing process is mainly conducted by thermal effect of laser. And for UV laser, the polishing process is mainly conducted by the photochemical effect of laser [14]. The thermal polishing process means that the working piece absorbing laser energy to achieve melting flow, gasification removal or thermal stress removal. Laser photochemical polishing means that after laser irradiation on the surface of the material, the material directly absorbs photon energy to break the chemical bond of the material or destroy the structure of the lattice, so as to achieve the removal of the material.

The current research on laser polishing ceramics at home and abroad mainly focuses on the thermal effect in the process [15-18]. The reduction of the surface roughness was mainly by the grain growth and "melting peak filling" of polishing molten pool. Li Weibo obtained smaller surface roughness under optimized process parameters during the polishing of SiC ceramics with 800nm femtosecond laser [15]. The roughness of 2.5μm was realized by 30W Yb: YAG laser polishing of alumina ceramics [16]. The polishing process was mainly based on the thermal effects such as the melting of the ceramic pieces. Ji et al. reduced the surface roughness of ZrO2 ceramics to 2.84μm by 6ns pulsed laser, and the polishing process was mainly through the melting and evaporation [17] of the materials. Zhang [18] et al. carried out the polishing of alumina ceramics by 1064nm picosecond pulse laser, and by controlling the laser polishing process, the ceramic surface was recrystallized, and the surface roughness of ceramic could be reduced from 1.8μm to 0.32μm [18].

Owing to the brittleness of SiC ceramics, the heat stress during the polishing process by thermal effect of the laser would lead to the cracks of the ceramic pieces. The thermal stress was small in the process of laser polishing by photochemistry effect, and almost no cracks would be found after processing, which was especially suitable for high precision polishing of brittle ceramics. In recent years, some progress has been made in the polishing of alumina ceramics by 355nm UV laser has also made [19, 20]. In terms of material surface removal, LIU et al. [21] proposed multi-photon absorption effect to explain the energy absorption caused by the femtosecond laser processing on dielectric materials. Zhao Qingliang et al. [22] used femtosecond laser micromachining system to conduct theoretical and experimental research on the ablation characteristics of SiC ceramics, and analyzed the multi-photon absorption during laser processing of SiC ceramics.

Since the band gap energy of SiC ceramics is about 3eV, the infrared laser with low photon energy is easy to cause the thermal effect during the polishing process through multi-photon absorption. The single-photon energy for 355nm UV laser is higher, so it has more advantages in removing ceramic surface roughness by photochemistry effect. In order to further analyze the mechanism of UV laser polishing ceramics, so as to further reduce the thermal stress in the polishing process. This paper innovatively proposed the method of ultraviolet picosecond laser "cold polishing" with infrared laser as preheating source to promote the photon-absorption process. The roughness removal mechanisms and surface morphology by different process parameters during the ceramic polishing was studied, thus greatly optimize the ceramic surface quality and provide technical basis for realizing high efficiency and high precision polishing of SiC ceramics.

2. Experiment

2.1. Preparation and Characterization of Liners and Fillers

The SiC ceramic used in this paper with the characteristics of high wear resistance and high hardness belonged to high temperature resistant structural materials. The EDS of the cermic samples was shown in Figure 1, and its chemical composition is shown in Table 1. It can be seen from Table 1 that the SiC ceramic maintained high purity in the preparation process. The samples were cut into 50mm*50mm*10mm ceramic plates CNC scribing cutting machine. Before laser polishing, the plate washing water was used for cleaning, as shown in Figure 2. The original roughness of the samples measured by white light interferometer was 1.616μm.

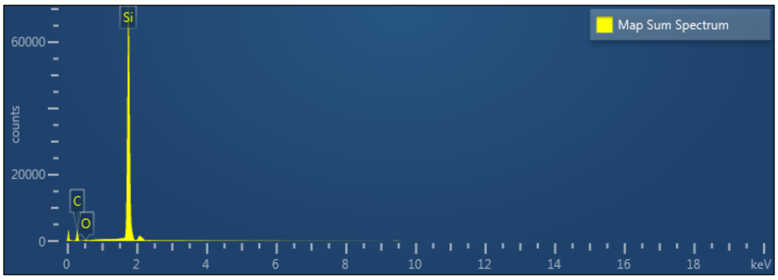
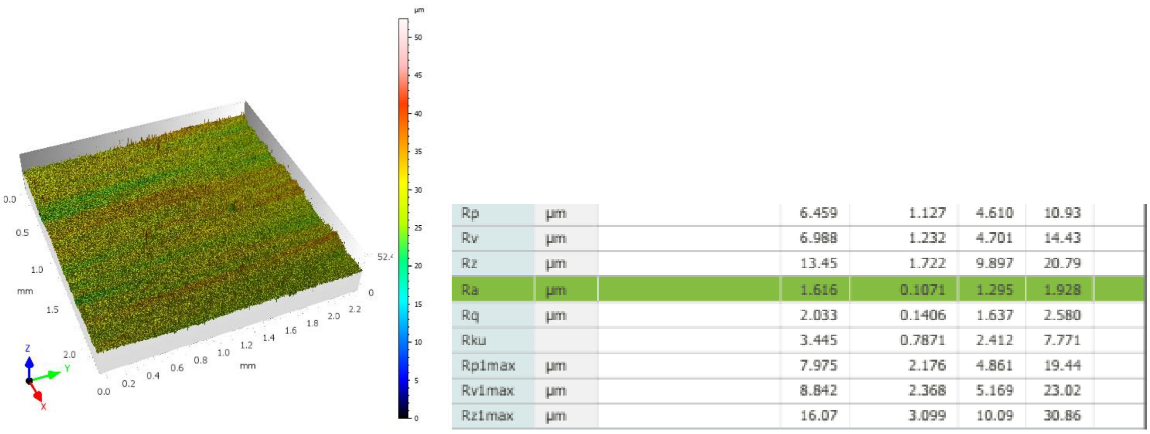


Figure 1. *EDS of the SiC ceramics.*

Table 1. *Chemical composition of SiC ceramic samples.*

Map Sum Spectrum			
Element	**Wt%**	**Wt% Sigma**	**Atomic %**
C	36.6	0.33	57.16
O	0.98	0.08	1.15
Si	62.41	0.33	41.68
Total:	100		100



Rp	µm	6.459	1.127	4.610	10.93
Rv	µm	6.988	1.232	4.701	14.43
Rz	µm	13.45	1.722	9.897	20.79
Ra	µm	1.616	0.1071	1.295	1.928
Rq	µm	2.033	0.1406	1.637	2.580
Rku		3.445	0.7871	2.412	7.771
Rp1max	µm	7.975	2.176	4.861	19.44
Rv1max	µm	8.842	2.368	5.169	23.02
Rz1max	µm	16.07	3.099	10.09	30.86

Figure 2. *Original surface morphology and roughness of samples.*

2.2. Laser Polishing Procedure

The 355nm UV picosecond laser polishing system is shown in 3, including 30W UV picosecond pulse laser, scanning galvanometer, beam shaping output mirror, five-axis CNC system, processing table, water cooling system, etc. The focal length of the UV laser is 170mm, as shown in Figure 4. The beam spot of the UV laser is a Gaussian spot with a diameter of about 1.8mm, and the beam diameter after the output focusing lens is about 40μm. The laser polishing process of SiC ceramic is shown in Figure 5. The single polishing area of SiC ceramic was adjusted to 5mm*5mm by scanning galvanometer. The power percentage of the UV laser was 20%-50% with the span of 10%. The scanning path spacing was 0.001-0.007mm with the span of 0.002mm. The scanning speed of the UV laser was 1200-1600mm/s with the span of 100mm/s. Orthogonal test was carried out by adjusting laser process parameters. At the same time, the effect of 800nm infrared continuous laser preheating on UV laser polishing of SiC ceramics was studied (as shown in Figure 6), and the mechanism of the surface roughness reduction due to photon absorption effect during SiC ceramic polishing was further analyzed.

The white light interferometer (BRUKER WYKO Contour GT-K) was used to directly measure the surface roughness of continuous laser polishing, and the 3D microstructure was obtained. The defects of the polished surface were further analyzed by optical microscopy. The microstructure and the metallographic of the polished workpiece was determined by ZEISS SIGMA 500/VP and GeminiSEM 300.

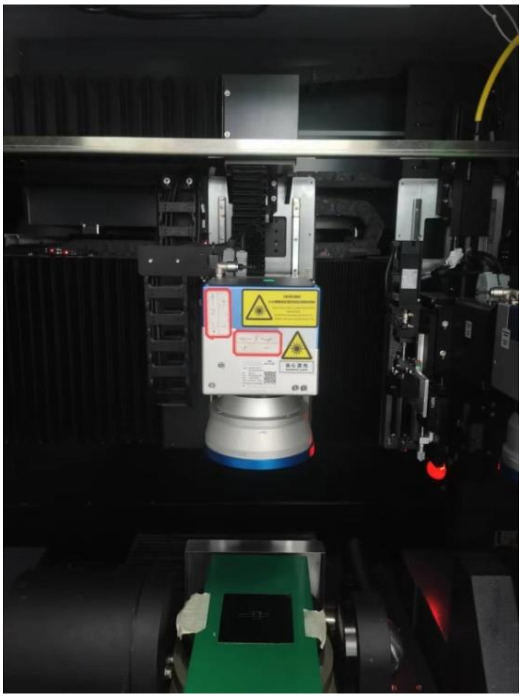


Figure 3. UV picosecond laser polishing system.

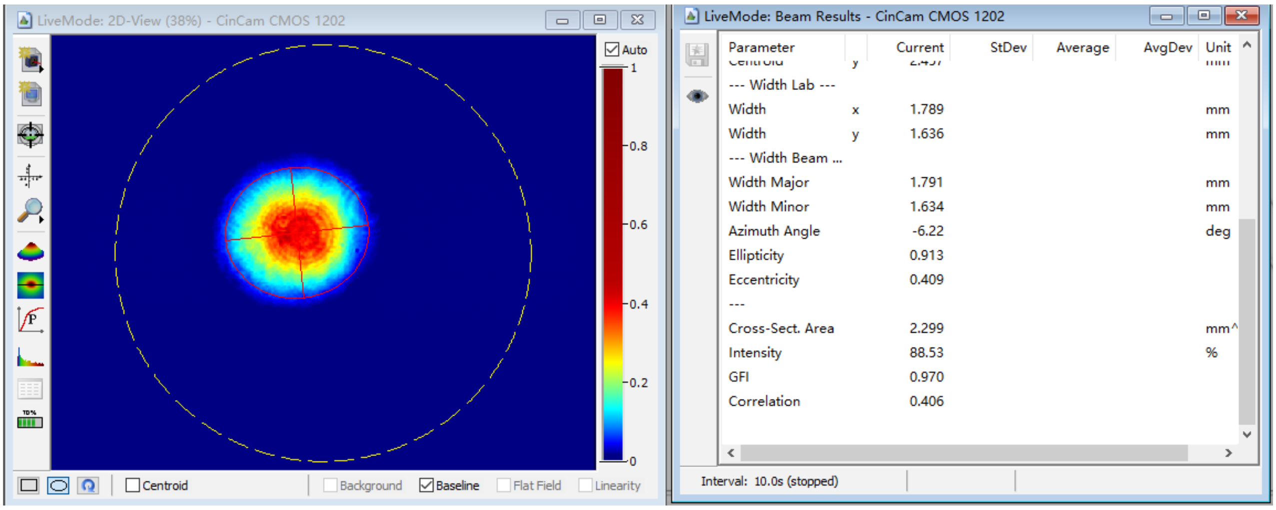


Figure 4. Beam spot of the UV laser.

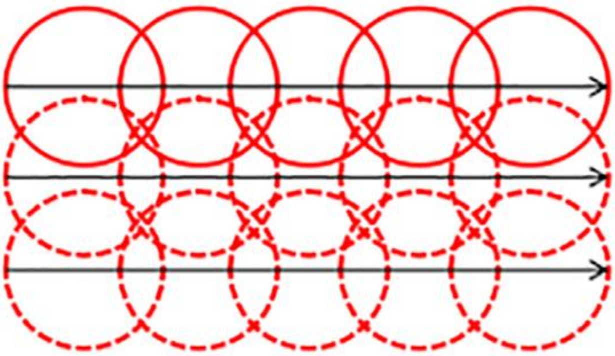


Figure 5. Schematic diagram of the UV laser polishing process.

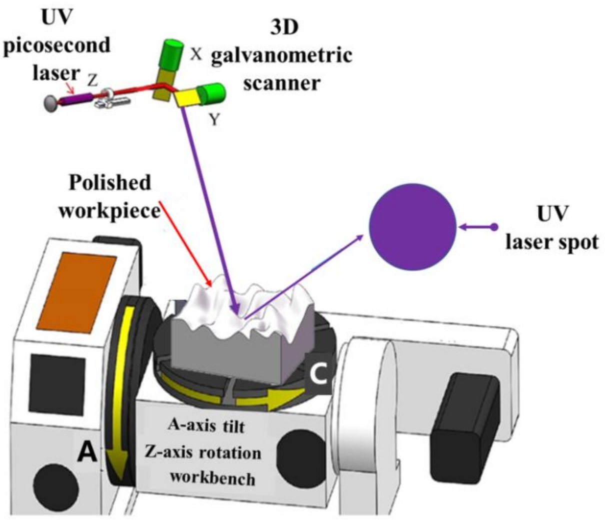


Figure 6. *Schematic diagram of the UV laser polishing process under the preheating of IR laser.*

3. Result and Discussion

3.1. Effect of Different Polishing Process on Surface Roughness by UV Laser

Figure 7 represents the surface of the pieces under different polishing processes with scanning speed of 1600mm/s. Roughness detection of polished samples under different UV picosecond laser parameters shows that the roughness Ra of SiC sample surface decreases first and then increases with the increase of laser power when the scanning spacing is unchanged, as shown in Figure 8. Figures 8 (a)-(d) represent the surface roughness of the polished sample with the scanning spacing of 0.003mm and the power percentage of 20%-50%.

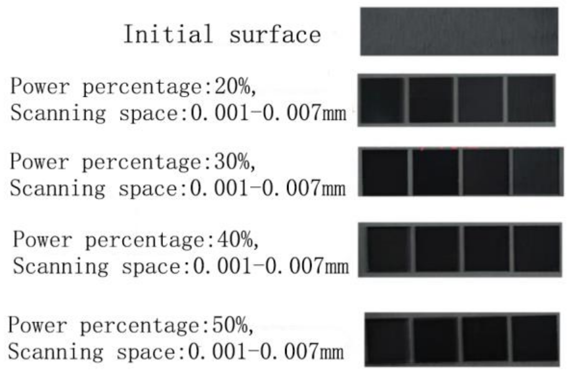


Figure 7. *Surface morphology of samples under different laser polishing processes.*

(a)

Rp	µm	6.597	0.9258	4.504	9.916
Rv	µm	5.799	1.014	3.679	9.837
Rz	µm	12.40	1.475	8.962	17.78
Ra	µm	1.421	0.1145	1.134	1.727
Rq	µm	1.804	0.1380	1.466	2.243
Rku		3.647	0.7471	2.541	9.972
Rp1max	µm	7.970	1.668	5.133	16.39
Rv1max	µm	7.223	1.944	3.755	16.40
Rz1max	µm	14.43	2.422	9.220	23.51

(b)

Rp	µm	5.000	1.188	3.618	12.92
Rv	µm	4.638	1.319	3.060	12.23
Rz	µm	9.639	1.871	7.030	19.55
Ra	µm	1.193	0.07587	1.022	1.491
Rq	µm	1.523	0.1435	1.278	2.120
Rku		3.957	2.021	2.225	16.55
Rp1max	µm	6.444	2.895	3.866	27.28
Rv1max	µm	6.194	3.088	3.340	22.39
Rz1max	µm	12.02	4.116	7.100	32.19

(c)

Rp	µm	4.997	0.9894	3.350	9.517
Rv	µm	4.806	1.232	3.079	11.45
Rz	µm	9.803	1.714	6.852	17.88
Ra	µm	1.155	0.1233	0.8910	1.822
Rq	µm	1.479	0.1927	1.149	2.757
Rku		3.847	1.239	2.618	13.30
Rp1max	µm	6.216	1.909	3.686	17.09
Rv1max	µm	6.536	3.155	3.332	25.04
Rz1max	µm	12.13	3.701	7.212	32.09

(d)

Rp	µm	5.863	1.067	4.147	12.15
Rv	µm	5.381	1.085	3.624	11.30
Rz	µm	11.24	1.580	8.215	18.42
Ra	µm	1.410	0.1426	1.127	1.835
Rq	µm	1.784	0.1993	1.423	2.737
Rku		3.496	1.059	2.370	10.19
Rp1max	µm	7.308	2.592	4.644	26.69
Rv1max	µm	6.814	2.434	3.878	22.98
Rz1max	µm	13.52	3.440	8.616	33.31

Figure 8. *Surface roughness of SiC under different laser power: (a) 20%; (b) 30%; (c) 40%; (d) 50%.*

Thermal phenomena such as material volatilization and surface destruction of brittle SiC ceramics appear at the beginning of the polishing process. And there was no "hot polishing" defects such as cracks, porosity in the microstructure of the polished ceramic samples detected by 200X optical microscope under different laser power (Figure 9). It shows that in the process of UV picosecond laser polishing, the cold polishing process of photon absorption was still the main process, but there was still the influence of laser thermal effect during the polishing process. The band gap energy of SiC ceramics is 3eV, and the single photon energy of 355nm UV picosecond laser is about 3.5eV, which meets photon absorption of the SiC ceramics. However, the thermal evaporation of the samples existed in the polishing process, which indicated that the thermal effect existed in the polishing process. This phenomenon is consistent with the results of previous studies [21, 22]. Therefore, when the power percentage was 20%, the laser heat accumulation process was accompanied by the ablation of the sample surface. When the power is gradually increased, it was easier to reach the threshold of multiphoton absorption effect, and the "cold polishing" effect was gradually obvious, and the roughness would be further reduced. When the laser power was too high, excess heat accumulation at the initial stage of polishing, which would lead to the melting and redeposition on the sample surface, and thus reducing the surface roughness. Figure 10 shows the 3D topography of the polished sample. It can be seen from Figure 10 that when the laser power increased from 20% to 30%, the surface roughness would be reduced due to the obvious "cold polishing" effect. However, when the laser power further increased, the ablation effect of heat accumulation would form volatile deposition on the sample and increase the surface roughness.

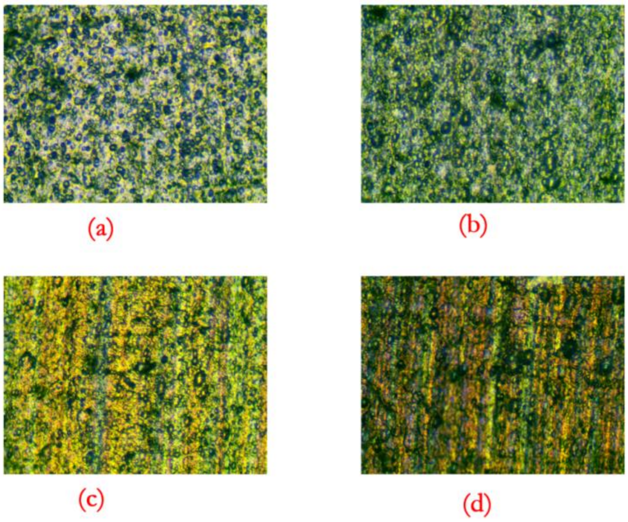


Figure 9. *Surface morphology of SiC ceramic under different laser power: (a) 20%; (b) 30%; (c) 40%; (d) 50%.*

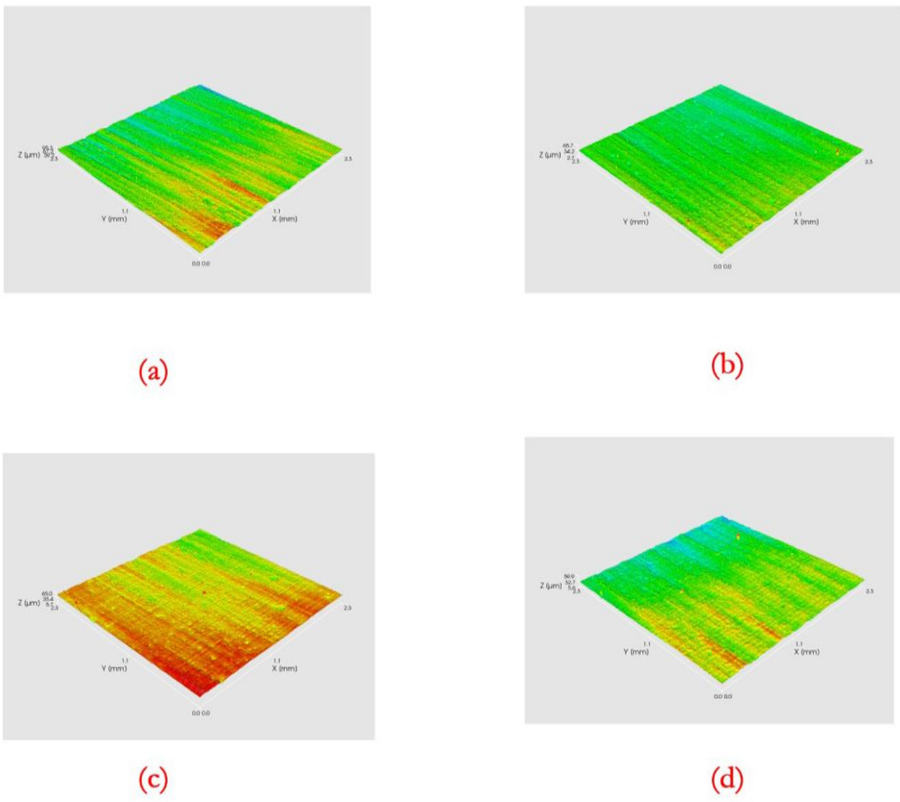


Figure 10. *3D morphology of SiC ceramic surface under different laser power: (a) 20%; (b) 30%; (c) 40%; (d) 50%.*

As shown in Figure 11, when the laser scanning speed was 1600mm/s and the laser power percentage was 20%, the roughness of the polished sample decreased first and then increased with the increase of the scanning speed. This experimental phenomenon can also be explained by the "cold polishing" threshold of photon absorption. When the laser scanning paths overlap, the previous laser polishing process would preheat the next polishing process, and the laser polishing process could achieve the "cold polishing" process of photon absorption faster, so as to achieve the reduction of surface roughness. Because the IR laser used in the experiment was a Gaussian beam, the preheating effect was obviously weakened when the laser scanning paths overlap less, and the thermal effect during the polishing process was more obvious, and the polishing quality of SiC ceramic with high temperature resistance and viscosity was weakened. In particular, when the laser power was lower than 10% and the scanning distance was 0.001mm, the heat accumulation effect was more obvious, and the surface quality was extremely deteriorated with the roughness of 3.707μm. Therefore, it can be seen that in order to improve the surface quality of SiC ceramics, it is necessary to reduce the heat accumulation as much as possible before the threshold of cold action polishing was reached.

Rp	μm	6.341	2.556	3.702	24.53
Rv	μm	4.670	0.7116	3.457	8.372
Rz	μm	11.01	2.872	7.828	30.24
Ra	μm	1.392	0.1760	1.065	2.230
Rq	μm	1.814	0.3569	1.330	4.005
Rku		4.029	2.204	2.496	18.30
Rp1max	μm	8.760	5.355	3.755	35.33
Rv1max	μm	5.737	1.645	3.507	17.13
Rz1max	μm	13.89	5.898	8.171	42.16

(a)

Rp	μm	5.000	1.188	3.618	12.92
Rv	μm	4.638	1.319	3.060	12.23
Rz	μm	9.639	1.871	7.030	19.55
Ra	μm	1.193	0.07587	1.022	1.491
Rq	μm	1.523	0.1435	1.278	2.120
Rku		3.957	2.021	2.225	16.55
Rp1max	μm	6.444	2.895	3.866	27.28
Rv1max	μm	6.194	3.088	3.340	22.39
Rz1max	μm	12.02	4.116	7.100	32.19

(b)

Rp	μm	5.436	1.168	3.587	10.84
Rv	μm	5.219	1.022	3.400	10.99
Rz	μm	10.66	1.625	7.814	18.23
Ra	μm	1.265	0.1044	1.065	1.629
Rq	μm	1.610	0.1497	1.328	2.223
Rku		3.803	1.236	2.602	10.61
Rp1max	μm	7.071	2.607	3.629	19.81
Rv1max	μm	6.503	1.934	3.611	14.20
Rz1max	μm	12.88	3.184	8.272	26.53

(c)

Rp	μm	5.730	1.017	3.914	9.800
Rv	μm	5.233	0.8670	3.729	8.257
Rz	μm	10.96	1.409	8.303	16.24
Ra	μm	1.404	0.07132	1.226	1.588
Rq	μm	1.743	0.09058	1.526	2.013
Rku		3.178	0.7299	2.311	9.716
Rp1max	μm	7.312	2.121	4.435	20.51
Rv1max	μm	6.462	1.837	3.958	14.85
Rz1max	μm	13.09	2.727	8.779	25.37

(d)

Figure 11. *Surface roughness of SiC ceramics at different scan spacing: (a) 0.001mm; (b) 0.003mm; (c) 0.005mm; (d) 0.007%.*

3.2. Effect of IR Laser Preheating on UV Laser Polishing of SiC Ceramics

Similarly, in the experimental process of UV laser polishing under IR laser preheating, the roughness can also be reduced to 0.66μm by adjusting the preheating process. Since there would be a good prospect in the field of semiconductor technology for SiC ceramics, the dual laser polishing of SiC ceramic substrates with the roughness about 0.16μm was also investigated. With the optimized UV laser parameters, it was found that the preheating process would improve the surface quality of SiC substrates. The roughness of about 0.025μm was achieved by the UV laser with the optimized parameters. Nevertheless, under the preheating of IR laser, the roughness of about 0.20μm was achieved.

4. Conclusion

(1) The orthogonal test results showed that when the laser power percentage was 30%, the scanning path spacing was 0.005mm, and the laser scanning speed was 1600mm/s, the surface roughness was further reduced from 1.616μm to 1.087μm. Compared with the traditional mechanical polishing process, the polishing efficiency was significantly increased by more than 3 times.

(2) The laser polishing process was accompanied by the "cold polishing" and "hot polishing" process. The experimental results showed that the polishing process of SiC ceramics by 355nm UV picosecond laser mainly exhibits two forms: material gasification and surface material removal after the photon absorption effect. By optimizing the laser polishing parameters, the "photon absorption" effect during polishing process can be realized faster, and the surface roughness of SiC ceramics can be effectively reduced by reducing the heat accumulation effect.

(3) The UV laser polishing of ceramic pieces under the preheating of IR laser was proposed. By adjusting and optimizing the infrared laser preheating parameters, the ceramics can be polished with high efficiency and high quality.

Acknowledgments

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Conflicts of Interest

The authors declare no conflicts of interest.

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