

Article

Surface Morphology Evaluation and Material Removal Mechanism Analysis by Single Abrasive Scratching of RB-SiC Ceramics

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Abstract: Reaction-Bonded Silicon Carbide (RB-SiC) ceramics possessing excellent mechanical and chemical properties, whose surface integrities have an essential effect on their performance and service life, have been widely used as substrates in the core parts of aerospace, optics and semiconductors industries. The single abrasive scratching test is considered as the effective way to provide the fundamental material removal mechanisms in the abrasive lapping and polishing of RB-SiC ceramics for the best surface finish. In this study, a novel single abrasive scratching test with an increasing scratching depth has been properly designed to represent the real abrasive lapping and polishing process and employed to experimentally investigate the surface integrity regarding different scratching speeds. Three typical and different material removal stages, including the ductile mode, ductile–brittle transition mode and brittle mode, can be clearly distinguished and it is found that in the ductile material removal stage by increasing the scratching speed would inhibit the plastic deformation and improve its surface integrity. It is also found that in the ductile–brittle transition and brittle material removal stages, to increase the scratching speed would inhibit the plastic deformation due to the fast scratching speed that limits the time of plastic deformation on the target, but it also results in the increased length of lateral cracks with the increased scratching speed which can reflect that the size of brittle chips, like brittle fractures and large grain fragmentations, increases as the scratching speed increases. It can provide the references for the optimization of the abrasive lapping and polishing of RB-SiC ceramics with high efficiency and surface quality.

Keywords: surface morphology; material removal mechanism; reaction-bonded silicon carbide ceramics; abrasive scratching



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1. Introduction

Due to the distinct mechanical and chemical properties of high erosion and wear resistance, high thermal conductivity, high chemical inertness and low thermal expansion, Reaction-Bonded Silicon Carbide (RB-SiC) ceramics have become the primary structure and substrate materials necessary for the aerospace, optics and semiconductors industries [1–3]. However, the inherent characteristics of high hardness and low fracture toughness bring large challenges in the machining of RB-SiC ceramics, and the surface integrity has an essential influence on their performance and service life in practice. Abrasive machining, as one of the non-traditional machining technologies, is a process to remove material by means of micro-ploughing, micro-cutting, micro-fatigue and micro-cracking, and has been extensively used to machine almost any material, particularly hard brittle materials [4–7]. Currently, the flat substrates of hard brittle materials, like RB-SiC ceramics, are usually

prepared by using the abrasive lapping and polishing processes [8,9], and to ensure the machining efficiency and quality, the optimization of processing parameters is necessary by conducting and repeating associated experiments many times, which is to some extent time-consuming and expensive. The single abrasive scratching test is considered one of the effective ways to investigate the fundamental of material removal mechanisms and provides good references for the abrasive machining process [10–13].

For hard brittle materials like RB-SiC ceramics, brittle material removal mode usually dominates the erosion process in terms of cracks and fractures, while by properly controlling the machining process the ductile material removal mode can be also found in removing hard brittle materials in terms of micro-cutting and micro-ploughing [14,15]. Rao et al. [16] employed the Vickers indenter to scratch the RB-SiC ceramics at elevated temperatures and found that the material deformation and adhesive behavior enhanced the ductile material removal and the coefficient of friction at elevated temperatures. Klecka and Subhash [17] investigated the scratch-induced damage in alumina ceramics by considering the different grain sizes and found that the intergranular fracture and grain dislodgement significantly contributed to the lateral crack propagation and resultant material removal from the target surface. Moreover, the multi-scratching tests were conducted by Yang et al. to reveal stress interaction and crack propagation behavior of glass ceramics and it was found that the material removal mechanism was distinctly related to the value and orientation of stress [18].

Most of the current research work on exploring the material removal mechanisms during the scratching process are either employing the nanoindentation or relatively low scratching speed at nanoscale, but in the abrasive lapping and polishing process the speed of abrasive particle scratching on the target surface is relatively large and the scratching depth is varied due to the different pressures on the target surface. Thus, in this study, a novel single abrasive scratching test on RB-SiC ceramics with an increasingly scratching depth will be designed to experimentally investigate the surface integrity regarding different scratching speeds with the assistance of high-tech measuring instruments, and it aims to provide the references for optimizing the abrasive lapping and polishing of RB-SiC ceramics with high efficiency and surface quality.

2. Experimental Work

2.1. Preparation of RB-SiC Ceramic Sample

The RB-SiC ceramic sample with dimensions of 10 mm × 10 mm × 3 mm is selected as the target and the major material properties of RB-SiC ceramics are given in Table 1. In order to guarantee the scratching stability of these samples in the experiment it is necessary to make the inlaid treatment for them, as shown in Figure 1, where the sample is embedded into the cylinder inlaid materials that is fixed by the gripping tong during the scratching process. After the inlaid treatment of the sample, the surface of the sample was first lapped parallel to the surface of the cylinder inlaid materials with P2400 sandpaper, and then it was polished by using the diamond slurry with concentration of 10% by mass and diameters of 2.5 µm and 1 µm, respectively, to realize the surface roughness of about 200 nm, which facilitates for further observation and analysis.

Table 1. Material properties of RB-SiC ceramics.

Density (g/cm ³)	Elastic Modulus (GPa)	Fracture Toughness (MPa·m ^{1/2})	Mohs Hardness	Bending Strength (MPa)
3.08	430	3.5	9.5	490

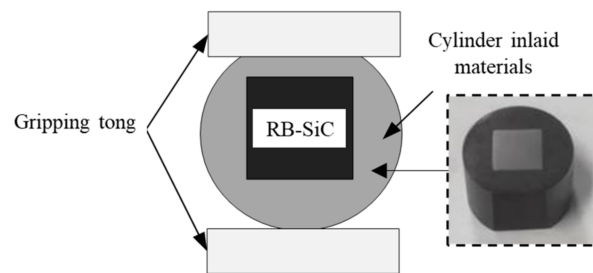


Figure 1. Inlaid treatment of the RB-SiC ceramic sample.

2.2. Experimental Setup

The experimental setup for the single abrasive scratching of RB-SiC ceramics is presented in Figure 2, where the specialized design cutting tool was connected to the spindle of the VMX42SRTi (Hurco Companies Inc., Indianapolis, IN, USA) CNC machine with the maximum spindle speed of 12,000 r/min and the cylinder inlaid sample was put just under the PCD cutter and fixed by the gripping tong. Then, the micrometer was employed to adjust the gripping tong to make it parallel to the working platform for ensuring the accuracy of the experiment.

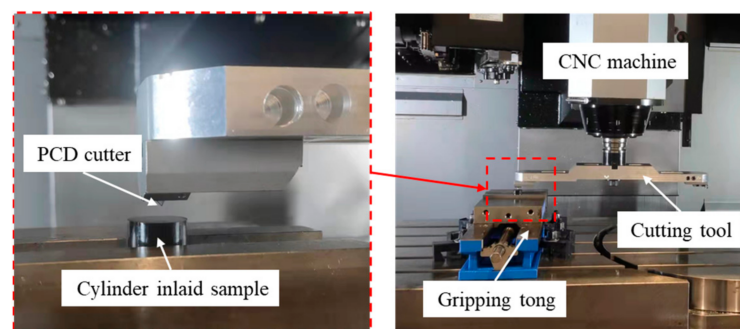


Figure 2. Experimental setup.

To be specific, as shown in Figure 3, the diameter of the specialized design cutting tool was 250 mm, which was large enough to realize the approximately straight scratching line on the target surface, and the triangle single blade PCD cutter (TPGH110302, Kyocera, Kyoto, Japan) with fillet radius of 200 μm was fixed in the bottom of the one side of the cutting tool, while on the other side, the same balancing weight was added in order to keep the stability during the rotating process with the relatively high speed. In the experiment, the single abrasive scratching test with an increasing scratching depth (d_c) from 0 to 30 μm was designed to facilitate the observation of ductile, ductile–brittle transition and brittle material removal modes on the target surface in a single scratching test. Moreover, due to the large mass and rotational inertia of the cutting tool and the consideration of the experimental safety, three levels of scratching speed (v_s) were selected at 1 m/s, 5 m/s and 10 m/s, respectively, by properly controlling the rotation speed of the spindle and the feeding speed in the CNC machine. Each test was repeated 10 times and the average data were taken. After each test, the sample was treated by putting it into the ultrasonic cleaner with the alcohol for 15 min and with the assistance of Zeiss SIGMA VP FE-SEM and Keyence VHX-7000 3D Microscope the surface morphology of the scratched sample can be observed for further comparison and analysis.

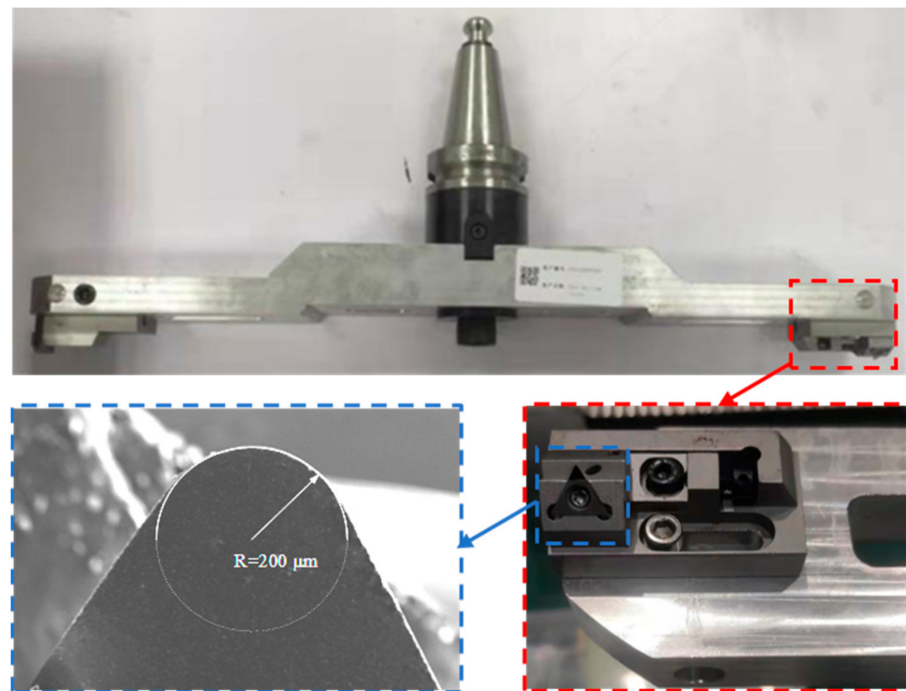


Figure 3. Specialized design cutting tool.

3. Results and Discussion

3.1. Overall Observation of the Surface Morphology

The overall surface morphology of the original RB-SiC ceramic sample after the precision abrasive polishing process can be seen in Figure 4, where the SiC and Si grains can be clearly found on the sample surface (see Figure 4a) and a good surface finish with the roughness of about 200 nm can be measured from Figure 4b, so that by using this kind of sample it facilitates the further distinguishing of the scratched sample surface with different material removal mechanisms. Due to the high hardness and brittleness of RB-SiC ceramic, it presents the typical brittle dominated material removal mode, such as the transgranular and intergranular cracks, as compared with the metals during the machining process [19,20]. However, by properly controlling the machining parameters the ductile material removal from RB-SiC ceramics with good surface finish can also be realized and the single abrasive scratching test is considered as one of the effective ways to investigate this phenomenon and to provide good references for the machining process.

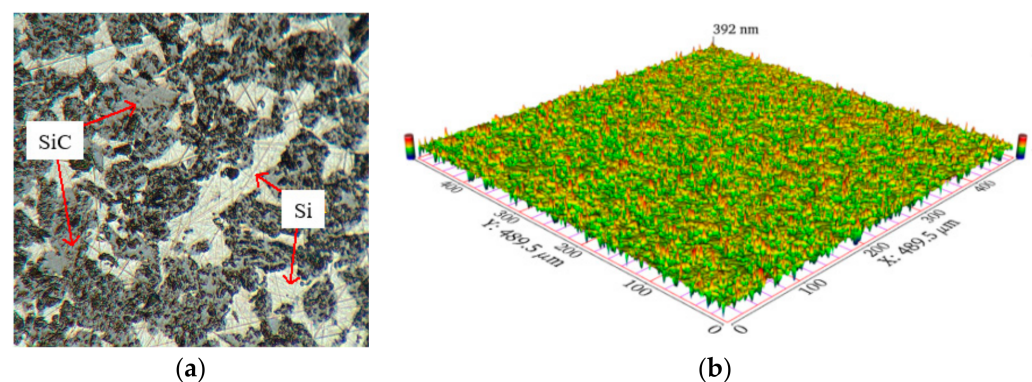


Figure 4. Surface morphology of the original sample. (a) 2D view; (b) 3D view.

Figure 5 shows the typical surface morphology of the gradually increasing scratched RB-SiC ceramic sample from $d_c = 0$ to $d_c = 30 \mu\text{m}$ at $v_s = 10 \text{ m/s}$ and three material

removal stages can be distinguished with respect to different underlying material removal mechanisms. In the ductile material removal stage, it can be seen from Figure 5 that a shallow scratched groove is left on the target surface and the surface of the groove seems to be smooth. Like the material removal from metals, RB-SiC ceramics are removed by plastic flow in this ductile material removal stage. To be specific, some materials can generate continuous thin chips in front of the rake face of the cutter and others can accumulate on both sides of the scratched groove to form plastic uplift such that there is almost no damage on the target surface [21,22]. After entering into the ductile–brittle transition material removal stage, the brittle material removal mode, like cracks, begins to dominate the material removal process, which results in the decrease of the smoothness on the scratched target surface. With the further increase of the scratching depth, it goes into the brittle material removal stage, where the width of the scratched groove significantly increases and there are obvious brittle fractures at the edge of the scratched groove caused by the grain spalling and fragmentation. Thus, in order to further analyze the material removal mechanisms in different stages, the surface integrity under different scratching speeds has been observed and compared, as explained in Section 3.2.

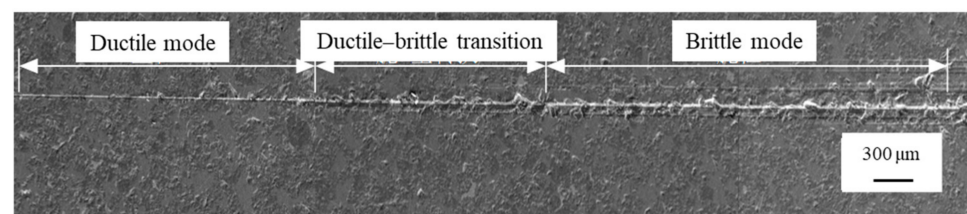


Figure 5. Overall surface morphology of the scratched RB-SiC ceramic sample at $v_s = 10$ m/s.

3.2. Evaluation of the Surface Integrity at Different Material Removal Stages

The surface integrity at different material removal stages with corresponding scratching speeds can be evaluated by distinguishing the surface morphologies of the scratched RB-SiC ceramic samples, as shown in Figure 6.

In the ductile material removal (DR) stage, as can be seen from Figure 6(a-i,b-i,c-i) the interaction between the cutter and target surface is mainly caused by plastic deformation with plastic flow and it is because the scratching depth is less than the critical depth of the ductile–brittle transition of RB-SiC ceramic so that the ductile material removal mode dominates the material removal process in the DR stage. It is also found, by comparing these figures, that the surface integrity has been improved with the increase of scratching speed from 1 m/s to 10 m/s in the DR stage. When the scratching speed is 1 m/s, the plastic uplift on both sides of the scratched groove is obvious, while the plastic uplift on both sides of the scratches at $v_s = 5$ m/s and $v_s = 10$ m/s is relatively slight. It is attributed to the fact that with the increase of the scratching speed the initiation of cracks can be effectively inhibited due to the limited generation of plastic deformation, hence resulting in the narrower scratched groove with a shallower depth.

In the ductile–brittle transition material removal (D-B-TR) stage, it can be seen from Figure 6(a-ii,b-ii,c-ii) that the plastic flow, brittle crack and fracture can be clearly observed on the scratched target surfaces; in this stage the scratching depth is just near the critical depth of the brittle–ductile transition of the RB-SiC ceramic, where both ductile and brittle material removal modes contribute to the material removal process. By observing the surface morphologies under different scratching speeds, it can be found in the D-B-TR stage that when the scratching speed is 1 m/s there is obvious plastic flow on the left side of the scratched groove and the brittle cracks occur on the right side of the scratched groove (see Figure 6(a-ii)). When the scratching speed increases to 5 m/s, the plastic uplift caused by the plastic flow and obvious cracks could be observed from Figure 6(b-ii) on the target surface. When the scratching speed further increases to 10 m/s, due to the existence of micropores on the target surface of the RB-SiC ceramic, the brittle fracture generated by the

initiation, propagation and intersection of cracks can be found on the scratched surface and the radial crack with a short length can be observed from Figure 6(c-ii) as well.

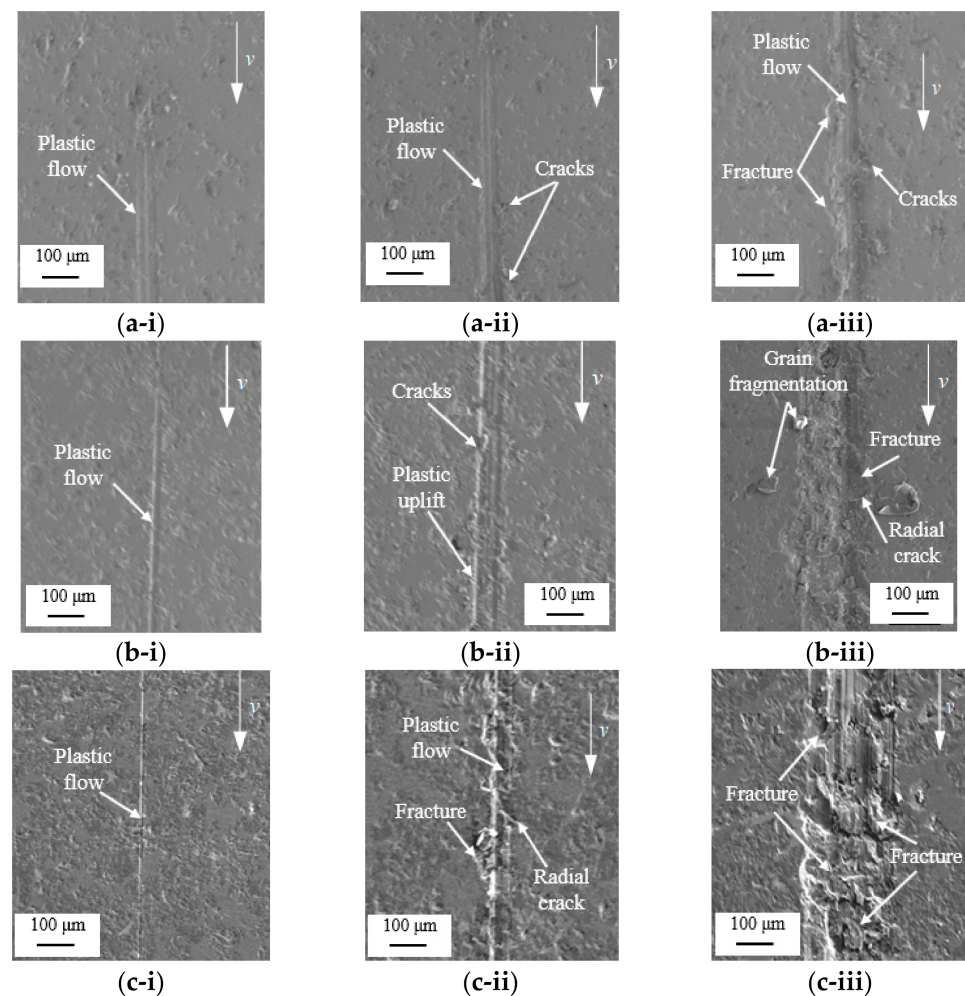


Figure 6. Surface integrity of the scratched RB-SiC ceramic sample at different material removal stages with corresponding scratching speeds. (a-i) DR stage, $v_s = 1$ m/s; (a-ii) D-B-TR stage, $v_s = 1$ m/s; (a-iii) BR stage, $v_s = 1$ m/s; (b-i) DR stage, $v_s = 5$ m/s; (b-ii) D-B-TR stage, $v_s = 5$ m/s; (b-iii) BR stage, $v_s = 5$ m/s; (c-i) DR stage, $v_s = 10$ m/s; (c-ii) D-B-TR stage, $v_s = 10$ m/s; (c-iii) BR stage, $v_s = 10$ m/s.

In the brittle material removal (BR) stage, the overall scratching depth is larger than the critical depth of the ductile–brittle transition of the RB-SiC ceramic, and the brittle fracture mainly contributes to the material removal in this stage, as can be observed from Figure 6(a-iii,b-iii,c-iii). Generally, in the BR stage the median crack can be formed at the bottom of the plastic zone and the radial crack can be generated on the target surface during the scratching process, while the lateral crack is usually formed after the scratching process due to the unloading residual stress, so that the initiation, propagation and intersection of median, radial and lateral cracks could result in the large brittle fracture on the target surface [23,24]. To be specific, when the scratching speed is 1 m/s, obvious cracks and fracture can be observed from Figure 6(a-iii) on the edge of the scratched groove. As the scratching speed increases to 5 m/s, the grain fragmentations caused by the intersections of transgranular and intergranular cracks are found along the scratching groove with some radial cracks as shown in Figure 6(b-iii). With the further increase of the scratching speed to 10 m/s, the resultant increased length of lateral cracks causes more brittle fractures that significantly dominate the material removal process, as can be found both on the bottom and the edge of the scratched groove in Figure 6(c-iii), as similar findings in Ref. [25].

To sum up, in the DR stage, with an increase of the scratching speed it would reduce the generation of plastic flow under the scratched groove and thus inhibit the plastic deformation and improve its surface integrity. In contrast, in the D-B-TR and BR stages, although to increase the scratching speed would inhibit the plastic deformation, it can also result in the increased length of lateral cracks in the abrasive target contact zone, which may facilitate the initiation, propagation and intersection of cracks to form the brittle fractures and the large grain fragmentations on the target surface.

4. Conclusions

The single abrasive scratching test can provide the fundamental material removal mechanisms in the abrasive lapping and polishing of RB-SiC ceramics, which can be used to optimize the associated processing parameters for the best surface finish. In this paper, a novel single abrasive scratching test with an increasing scratching depth from 0 to 30 μm has been properly designed to represent the real abrasive lapping and polishing process and has been employed to experimentally investigate the surface integrity regarding different scratching speeds. Three typical and different material removal stages, including the ductile mode, ductile–brittle transition mode and brittle mode, can be clearly distinguished by observing the surface morphology after the single abrasive scratching test with the assistance of high-tech measuring instruments. To be specific, it is found that in the ductile material removal stage, by increasing the scratching speed it would inhibit the plastic deformation and improve its surface integrity. It is also found that in the ductile–brittle transition and brittle material removal stages, although to increase the scratching speed would inhibit the plastic deformation, it can also result in the increment of the length of lateral cracks in the abrasive target contact zone that can induce the initiation, propagation and intersection of cracks to form the typical brittle fractures and large grain fragmentations on the target surface. However, it is also noticed that the large grain fragmentations and brittle fractures would result in materials being removed from the target surface, which could have an effect on the subsequent scratching process; this effect is worth investigating in the future work. Therefore, the findings in this paper can provide the references for the abrasive lapping and polishing of RB-SiC ceramics that by properly controlling the abrasive lapping and polishing pressure and speed it can realize the brittle material removal with high efficiency and ductile material removal with high surface quality.

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