Single diamond grit scratch tests of Silicon Carbide ceramics

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Scratch tests of SiC ceramics are carried out using a diamond fly-cutting machine tool. The formation, expansion and intersection of cracks are investigated as well as the influence of grit wear on scratch status. According to the experimental results, ductile-to-brittle transition happens with the increase of cutting depth. Micro cracks appear along the edges and on the bottom of plastic groove in plowing stage. The normal force, tangential force, the width of scratch traces, and the length of surface cracks sharply increase as the scratch distance is longer than 1600mm. The cracks intersection is found promote to material broken.

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1. Introduction

SiC ceramics has excellent physical and mechanical properties such as high hardness, high specific stiffness, high elastic modulus, high wear resistance and high thermal conductivity with low density and low thermal expansion coefficient, furthermore, it can be well combined with coating materials, and can adapt to the harsh space environment [1-3]. All these properties make it popular and widely used in the application in field of defense and space optical systems, space telescope mirrors, laser weapons and satellite mirrors, etc. for example [4]. The application of SiC ceramics in these areas can reduce the weight of optical elements and improve the resistance dimensional changes brought by weightlessness and temperature. While the biggest problem which troubles people is the hard machinability. Grinding is a complex but effective machining method, especially for hard and brittle materials.

The main fracture mode in grinding process is brittle fracture, which introduces surface and subsurface damages, and the grinding wheel is seriously worn in long time machining. All these shortcomings limit the processability and machining efficiency of SiC elements. Numerous studies have been dedicated to the research of removal mechanism and wheel wear mechanism of SiC ceramics [5-7].

Many researchers have carried out studies in this field. Y Wang et al.[11, 12] investigated the wear and wear transition mechanism, their experimental results showed that the tensile stress at the rear edge of the contact caused by friction force was the predominant stress which causes the ceramics to crack and leads to a ductile to brittle transition, in addition, a modified fracture mechanics model was built to predict the critical tensile stress of the cutting transition. G Subhash [13] conducted variable-depth single-grit scratch experiments on alumina ceramics with three different grain size, and found that the ductile to brittle transition depth increased with the decrease of grain size, the damage zone size increased with the increase of grain size and depth of cut, an analytical predictable model of plastic zone size was built and was well compared with the experimental results. X. Chen et al. [14] used an acoustic emission system in single grit scratch tests to identify the energy foot prints of the three cutting stages to provide a different focus in obtaining efficient cutting conditions. T. T. Öpöz and X. Chen [15] conducted single grit scratch experiments on En24T steel using the CBN grit, the results showed that the material removal strength changed continuously during and the cutting ability of grit varied with cutting edge shape, furthermore, the characteristic of single edge scratches were different with that of multiple edges and the material removal was more prominent at the entrance side of the scratch. D. Giridhar and L. Vijayaraghavan et al. 16] conducted scratching experiments on sintered alumina considered with parameters such as inclination angle of the indenter, grooving speed and normal load. They found that ceramics was prone to median and lateral cracks in scratching process, and reasonable parameter combination would lead to ductile cutting mode, for example, with normal load of 10 N, combined with 5° angle of inclination and a scratching speed of 20mm/sec. V Singh and S Ghosh et al. [17] compared the specific plowing energy requirement of ductile material and brittle material, and found that the cutting depth played an important role in "size effect".

In view of these lectures, most of the scratch tests are focused on the pile up of ductile materials or the ductile-to-brittle transition of brittle materials and the influence of different machining parameters with single abrasive. The interaction effect of adjacent grits on the removal mechanism is hardly any studied. Additionally, with the widely application of large scale mirror of SiC ceramics, the badly wear of grinding wheel has seriously influenced the surface quality and form accuracy, while single abrasive wear research which is the basic study of grinding wheel while the related research is seen seldom.

Therefore, in this paper, the inclined scratch test and the multi parallel scratch test are conducted to reveal the mechanism of crack formation and expansion and the removal mode transition of SiC ceramics; the influence of diamond grit wear on surface quality and the interaction of adjacent grits are investigated.

2. Experimental

2.1 Materials and Indenter

The pressureless sintering SiC ceramics is used, and the physical characteristics are shown in Table 1. The SiC specimens are cut into pieces with size of 10mm×10mm×2mm by a surface grinding machine with diamond cutting wheel, the scratching surfaces of the specimens are polished.

The diamond indenters of Vickers hardness are used in these experiments, as shown in Fig.1. The mode of indenters is HV-6, with an angle of 135°.

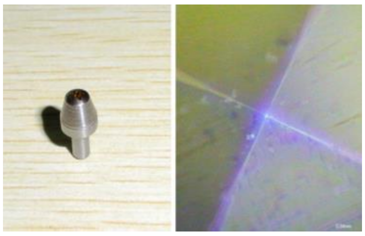

Fig. 1. Diamond indenter of Vickers hardness used in experiments.

2.2 Experimental equipment and experimental parameters

A diamond fly-cutting machine tool is used to carry out the experiments, shown in Fig. 2. There are three advantages of this machine tool. Firstly, the high alignment accuracy can be maintained with the high rotation accuracy of the machine tool; Secondly, the diameter of the cuter head is 500mm, so the scratches of the SiC ceramics specimen can be considered as straight lines. Thirdly, a micro feed mechanism is fixed on the cutter head, which can achieve a micron feed in the scribing process.

The detailed experimental parameters are as follows: The rotation speed of cutter head of 480 rpm is used in both the inclined scratch test and the multi parallel scratch test, so that the cutting speed can be calculated as 12.56m/s. The cutting depth in multi parallel scratch test is 15μm, and the transverse feed rate is 2mm/s, and a space of 250μm between the adjacent scratches is generated.

Table 1. Physical characteristic of pressureless sintering SiC ceramics.

Material	Elasticity modulus (GPa)	Fracture toughness (MPa • $m^{1/2}$)	Bending strength (MPa)	Coefficient of thermal expansion (×10^{-6}/K)	Density (kg/m^3)	Thermal conductivity (W/m • K)
SiC	410	3.2	410	4.7	3120	45

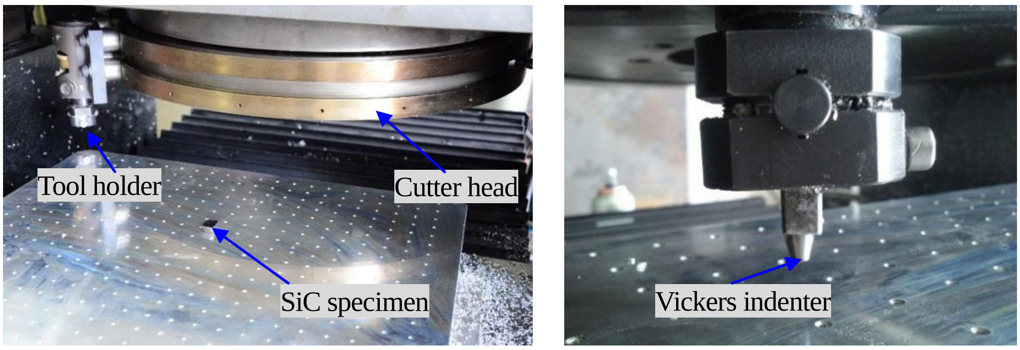

Fig. 2. The diamond fly-cutting machine tool.

2.3 Detecting method of subsurface cracks

A Cross Section Polisher is used to preprocess the scratched surface, and the principle is shown in Fig. 3 a), the ion beam is injected onto the edge of the specimen, and a polished surface is formed perpendicular to the scratched plant. The sub-surface cracks can be detected by the SEM from the polished surface. This method can effectively avoid secondary damage to the workpiece surface.

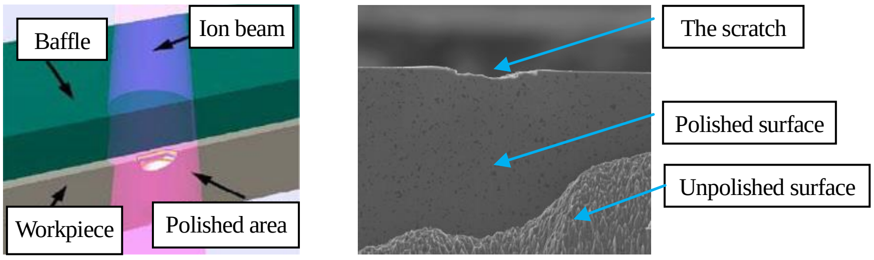

Fig. 3. Schematic diagram of workpiece pretreatment.

3. Results and discussion

3.1 Surface and subsurface cracks

In grinding process of SiC ceramics, because of the strong covalent bonding energy in SiC ceramics, the plastic deformation is very limited, therefore, the dislocation movement and slip movement are difficult to occur, and thus the brittle removal is dominant removal mode. In spite of this fact, there still ductile removal mode appears in grinding process when the cutting depth is extremely small.

The grinding depth of single diamond abrasive plays an important role in the material removal mode and is the key point of ductile-to-brittle transition. Inclined scratch of single abrasive is an efficient method to study the surface and subsurface crack formation, as well as the ductile-to-brittle transition of SiC ceramics, with the generally increasing of cutting depth from zero.

A single diamond abrasive with a certain cutting speed (12.56m/s in this paper) is used to conduct the inclined scratch. Compared with the quasi-static scratch and the indentation experiments, the influence of tangential force is considered, and the dynamic impact effect on material removal characteristics, the formation and expansion of cracks, as well as the material failure modes have been detected.

Fig. 4 shows laser scanning confocal micrograph photographs of the inclined scratch. The Fig. 4 a) is the overall conditions affected by the increase of cutting depth, from which it can be see that the cutting process is divided into three stages, including rubbing, ploughing and cutting, along the scratch direction from top to bottom of the picture. The sliding mark, plastic grooves, micro surface cracks and their propagation, as well as material fracture are observed. Fig. 4 b) shows the profile of three cross sections shown by the red line in Fig.4 a), the elastic recovery in rubbing stage, the plastic pile up and the depth of plastic groove in ploughing stage and the cracks in brittle removal mode are seen intuitively. In addition, the depth of grooves in three grinding stages which suggests the real cutting depth of single diamond grit is gained, as 0.15μm, 0.44μm and 1.32μm. Fig. 4 c) is the partial enlarged detail of the rubbing stage, in which a slight trace of diamond grit can be seen. Fig. 4 d) shows the partial enlarged detail of ploughing stage, in which a conspicuous plastic groove is observed. Obvious trace of diamond tip and tiny flakes are left around the blowhole defect in the bottom of the plastic groove. Compared with the ploughing stage in ductile materials grinding process, tiny cracks are generated along the both edges of groove. Fig.4 e) shows the partial enlarged detail of ductile-to-brittle transition area in the cutting stage, from which it can be seen that tiny cracks expand as large surface cracks, and then expand as fracture with the increase of cutting depth, so the brittle removal mode dominates the material removal process.

In the initial stage of characterization, the cutting depth of diamond grit is extremely shallow which causes low grinding force, and the elastic recovery of SiC ceramics is dominant, as a result. Swipe phenomenon occurs and no material removal and surface damage generate. From the No.1 profile in Fig. 4 b), it can be seen that there is hardly any cutting depth in scratch. As the increase of cutting depth, the friction force between diamond grit and SiC ceramics makes the interatomic dislocation and slip, which induces the cutting process getting into the plowing stage. In this stage, the plastic groove is formed, and the ductile removal mode can be seen as the same as that in ductile material cutting. From the profile of the No.2 cross section, plastic pile-up is observed. While from Fig. 4 a) and d), it can be seen that there are still micro cracks formed along the edges of plastic groove. The reason can be drawn that the tensile stress generated by the increased fractional force exceeds the critical tensile stress of SiC ceramics along the groove edges.

According to the study of T. G. Bifano, the critical depth of ductile-to-brittle transition mainly depends on the elastic modulus, fracture toughness and hardness, so it is very small because of the high hardness of SiC ceramics. Then, with the influence of high brittleness, the removal mode transforms form ductile mode to fracture crush quickly as the increase of diamond grit cutting depth. Long surface cracks and crushing surfaces caused by the interaction of cracks can be seen from Fig. 4 a) and e). Plenty of fine chunks of SiC ceramics are generated and detached from the main material which results in a broken surface. As shown in the profile of the No.3 cross section, wider scratch with a zigzag broken bottom is observed.

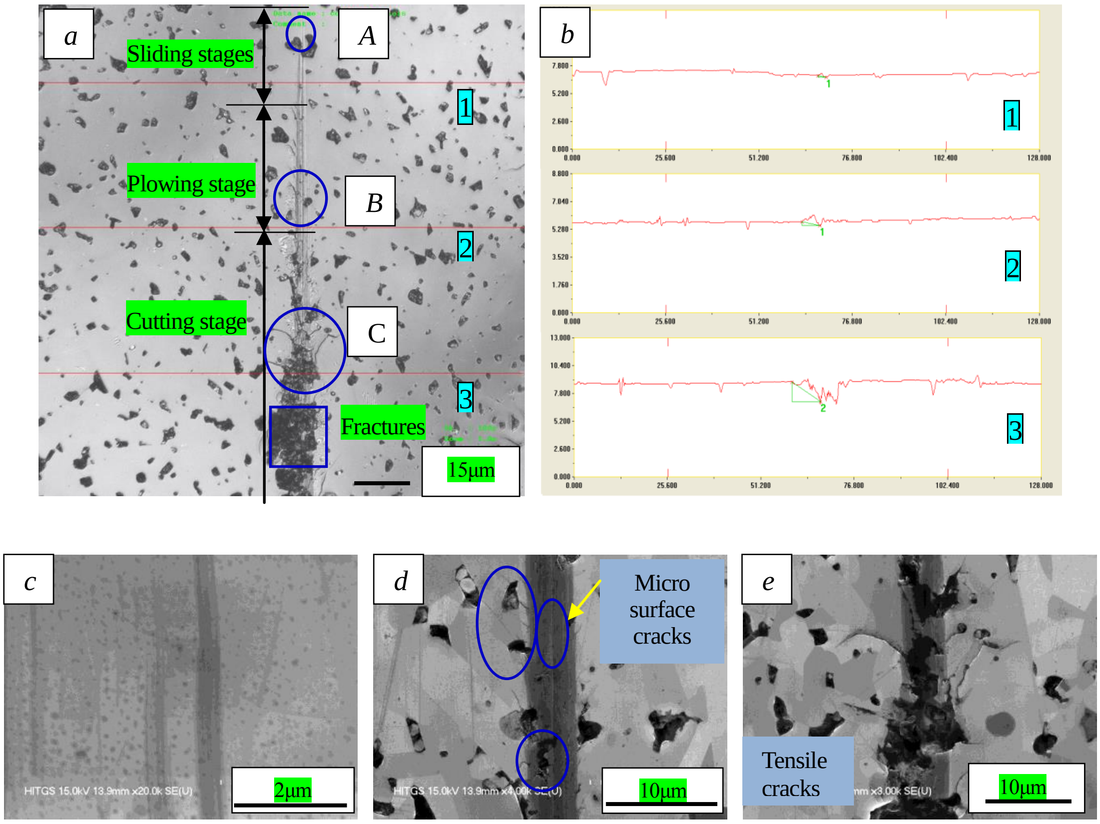

Fig. 4. Photograph of laser scanning confocal micrograph of the inclined scratch a) inclined scratch mark, sliding direction from top to bottom; b) the profile of the three cross sections in a); c) higher magnification of sliding stage in region A of a); d) higher magnification of plowing stage in region B of a); d) higher magnification of cutting stage in region C of a).

Subsurface cracks which must be avoided play an important role in evaluation of machining quality in grinding process of SiC ceramics, as they seriously affect the function and life of optical components. Fig. 5 shows the SEM pictures of subsurface cracks prepared by cross section polisher. Radial cracks and lateral cracks can be seen under the scratch trace surface. In addition, fine fractures, which are the result of expansion of surface cracks, are left over on the surface. Radial cracks which are the main composition of subsurface damage expand vertically or aslant directly down to the subsurface. The radial crack depth here is about 50µm with an angle about 45° in subsurface. There are plenty of lateral cracks with a shallow depth under the scratch surface. Most of these lateral cracks expand to surface and fracture chips generate with the influence of tensile stress, while the remaining cracks, which are several or dozens micrometers below the ground surface, make big problem for surface and subsurface quality. Longtime of polishing process is needed to remove these cracks, and this will extend the production cycle.

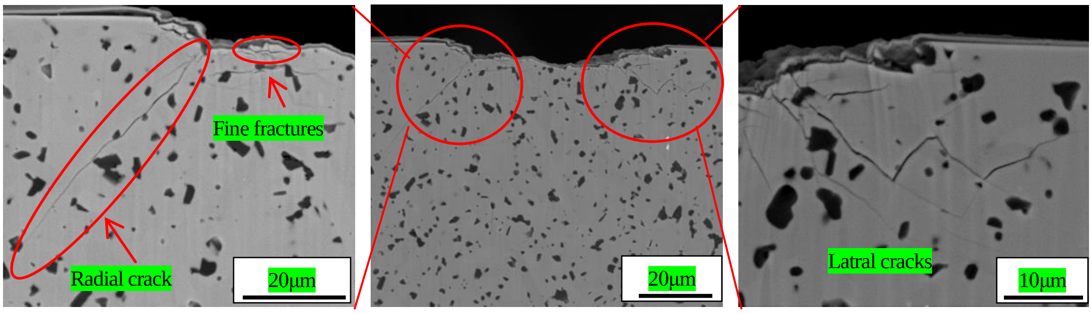

Fig. 5. SEM picture of subsurface cracks prepared by cross section polisher.

3.2 The influence of diamond grit wear on scratched surface

In grinding of hard and brittle materials process, a big problem which confused researchers is grinding wheel wear. It will reduce the grinding ability and surface quality. Study of single abrasive wear is a basic research means to understand the mechanism of grinding wheel wear. In this study, single abrasive scratches with fixed cutting depth (15µm in this paper) are carried out to study the influence of single abrasive wear on the formation and expansion of surface cracks and the grinding forces.

Fig. 6 shows the SEM photographes of scratch traces with different distance. As the cutting depth is much higher than the critical cutting depth of ductile-to-brittle transition, brittle removal mode is dominant in the scratch test. From Fig. 6 a) and b), plenty of micro cracks and tiny flaking are observed along the edges of scratch. It can be seen more clearly that the trace width gets larger in size, the length and density of cracks, as well as the extent of crushing get worse than that in the initial stage as the increase of scratching distance. The Fig.6 c) and d) are the traces in distance of 100mm and 800mm, the width increases and one more severe crashing surface is generated. Fig. 6 e) and f) are the partial enlarged detail of bottom of scratch trace. Fine particles and flaky tears from the left side can be seen on the bottom. Fig. 7 reveals the influence of scratch distance on normal force and tangential force of diamond grit in scratch test. It can be observed that both normal force and tangential force increase as the scratch distance increasing; a rapid increase happens when the scratch distance is longer than 1600mm and the width of scratch trace expands to over 120µm. Then it can be considered that the diamond grit is badly worn and cannot maintain stable cutting state. Wherefore, the sudden increase of grinding forces can be considered as an evaluation criteria of the grinding wheel wear.

Here are reasons of worse surface quality and larger grinding force can be explained as follows. The shape of diamond grit is cuspate so that it has strong cutting ability and is sharp enough to remove SiC ceramics materials at the beginning of scratching, while with the continues of scratching, the abrasion wear and micro broken (the two small traces in Fig. 6 f) are left by the micro cutting edges of the broken diamond grit) happen on the contact flat between diamond grit and SiC ceramics after long distance scratching. Therefore, the cutting capacity decreasing alongwith fraction force and extrusion force increasing is observed with the contact flat area increase caused by diamond grit wear. It is known that the stress concentration contributes to fracture failure of brittle materials and sharp diamond grit is better able to generate stress concentration than the worn grit. Tensile stress caused by fraction force is the key point for the expansion of cracks. It gets larger than the critical tensile stress of cracks expansion as the generally increasing of fraction force between diamond grit and SiC ceramics, which will tear the lateral cracks and radial cracks to form crashing surface. So it is important and essential to dress grinding wheel in grinding process regularly or online in order to make the worn grits fall off and be replaced by sharp ones.

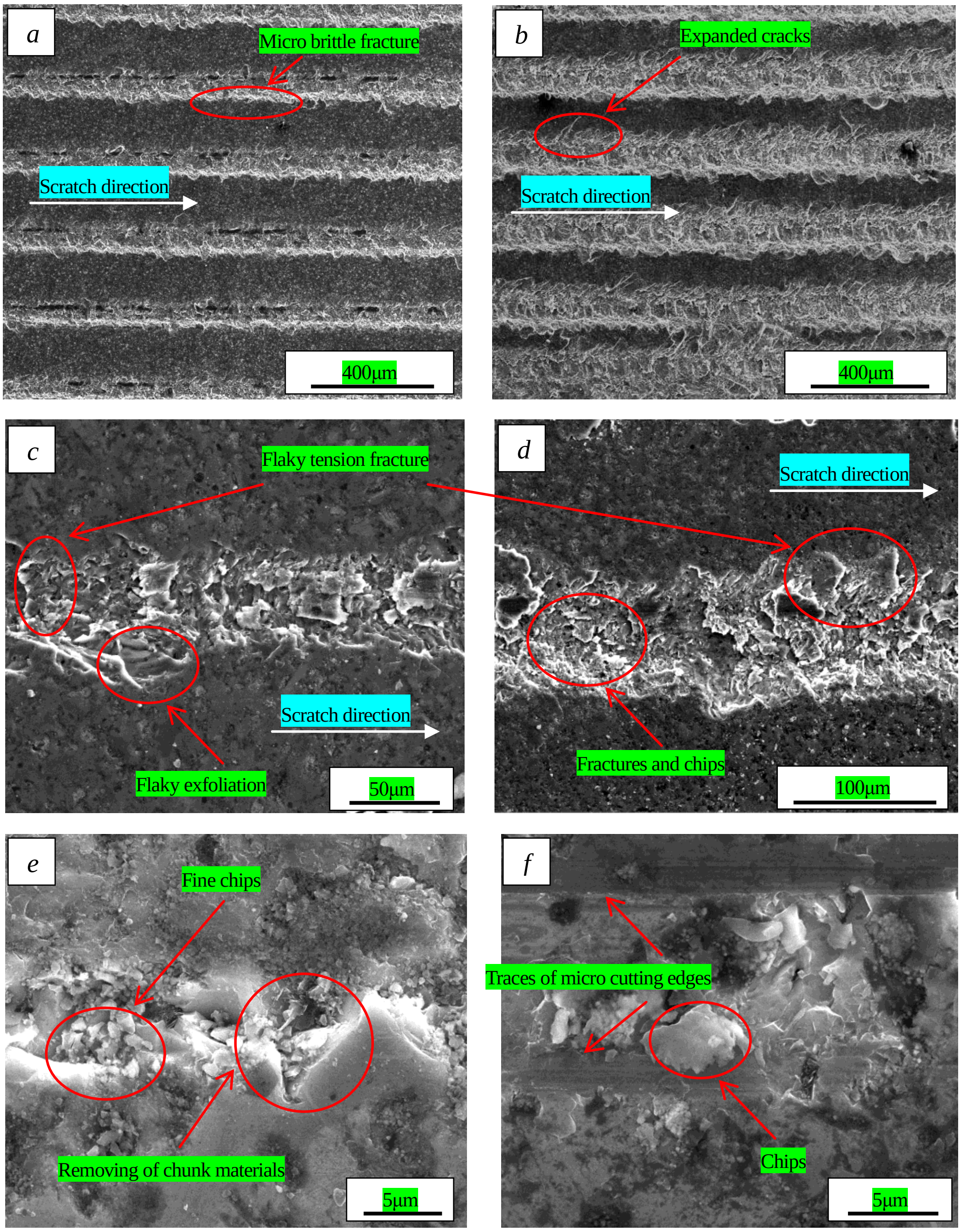

Fig. 6. SEM pictures of single abrasive scratch with different cutting distance a) traces in initial scratching stage, b) the traces with a distance of longer than 900mm, c) the single trace with distance of 100mm, d) single trace with distance of 800mm, e) and f) higher magnification of bottom of scratch.

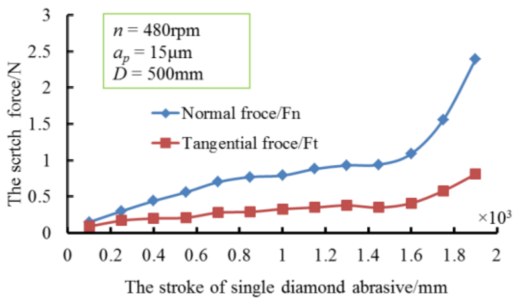

Fig. 7. Scratch forces influenced by scratching distance.

3.3 Cracks intersection of adjacent scratching traces

Approximately equally spaced parallel linear scratches are formed on the surface of SiC ceramics by the simultaneously control of the rotary speed of cutter head and the linear feed movement of machine tool guide. The scratching parameters are listed in Part 2.1. In grinding process of SiC ceramics, because of the small spacing between adjacent diamond grits on grinding wheel, the scratches of adjacent grits interact with each other, therefore, cracks and fractures intersect and affect the formation of the ground surface morphology. Thus, the purpose of this experiment is to reveal the interaction of the adjacent scratches.

Fig. 8 represents a SEM micrograph of scratches morphology. From the shape of the cracks, flaking and tears, it can be concluded that cracks are generated with the effect of extrusion and impact forces, and fracture happens in front of the scratching direction. Large numbers of lateral cracks and cone cracks are left both along the edges and on the bottom of scratch traces. The transfixion phenomenon can be found between the adjacent traces. Chunks of materials in the unscratched surface fall off and the uneven surface is generated. This intersection between cracks is beneficial to material removal; therefore it can reduce the cutting energy and tensile stress needed in machining process compared with single scratch process.

It can be observed that the interaction of adjacent grits can promote the formation and expansion of cracks; the intersection of cracks is conductive to the crushing and removing of SiC ceramics and improves the material removal efficiency. As a result, in the case of the assurance of enough space for holding chips, the inter-grain spacing should be reduced to promote the interaction between adjacent abrasive grains, such as improving the concentration of diamond grits.

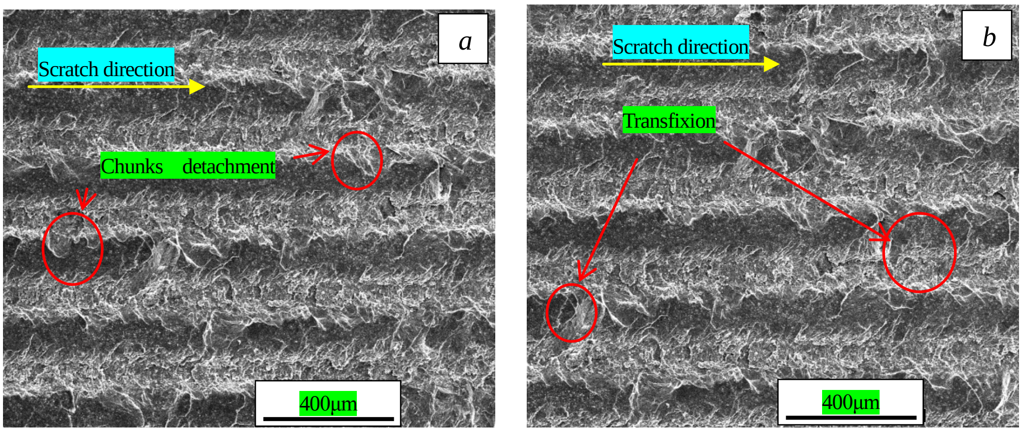

Fig. 8. SEM picture of multi parallel scratch test.

4. Conclusion

According to the results of single diamond grit scratch experiments carried out on a diamond fly-cutting machine tool, the following conclusions can be drawn:

Rubbing, plowing and cutting stages are observed in inclined scratch test. Ductile removal mode appears when cutting depth of diamond grit is small enough and translates to brittle removal mode quickly as the increase of cutting depth, then many tiny micro cracks along the edges and at the bottom of the plastic groove are appeared.

The diamond grit wear happens with the increase of scratch distance which reduced the cutting capacity of diamond abrasive, and leads to the increase of normal force and tangential force. The wear of diamond grit results in the formation and expansion of cracks and the fracture extent get worse, which leads to an even worse surface quality. The experimental results show that the diamond grit should be replaced as the scratching distance being longer than 1600mm. It is necessary to dress grinding wheels in order to make the worn diamond grit fall off the wheel.

The intersection of cracks generated by adjacent abrasives would promote the brittle fracture of SiC ceramics, increase the material removal rate and decrease the cutting force and cutting energy needed in grinding process. Hence grinding wheel concentration can be improved to promote the interaction between adjacent grins with the premise of enough chip space.

Acknowledgments

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