RESEARCH ON THE CRACKS EXTENDING MECHANISM OF GRINDING SILICON NITRIDE CERAMICS

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Using diamond wheels to grindingengineering ceramics is the most common method. Due to the large grinding resistance there is often a surface damage such as cracks on the workpiece. The crack depthmodel of grinding surface on ceramics is established based on indentation fracture mechanics in this paper and the extendingprocess of the crack is simulated by Two-Dimensional discrete element simulation of UDEC. Through simulation results the extending mechanism of cracks in silicon nitride ceramics is discovered. Moreover, the planegrinding experiment of silicon nitride ceramics by diamond wheel is carried out and the extending of its cracks is observed on the surface. The theoreticalresults are validated by grinding experiment. Cracks appear on the surface of the ceramics under the action of singlediamondgrain,theleadcrack extends along the interior of the ceramic in the form of longitudinal cracks. In the lead crack propagation path, a small amount of oblique cracks will appear in other directions. The failure zone consists of tensile failure element and shear failure element. The shear failure is main failure form for the failure zone. When the grain stops, the crack ceases to expand into the interior of the ceramic, the crack failure elements in the zone are all shear failure elements.Becauseof the grinding and tensile failure of the grinding wheel, the crack extends along the arc and the wheel direction of rotation in the contact area between the wheel and the ceramic. When the penetration depth increases, the crack form is gradually transformed from the tensile failure element to the shear failure element. The number of broken parts in the cut is obviously more than that of the cutting part. Grinding damage of engineering ceramics could be forecasted and controlled by this simulation. So, grinding process could be optimized, and grinding efficiency and quality could be improved.

Keywords:*diamond wheel, silicon nitride, surface damage, cracks, UDEC*

The lead crack extends toward deep of silicon nitride ceramic as longitudinal crack by extrusion effect of single diamond grain and there are small amount of oblique cracks in the other direction. Under the rotating grinding and tension damage, the cracks expand toward the rotation direction of diamond wheel along an arc in the contact parts between diamond wheel and silicon nitride ceramics. The amount of failure elements in the parts of cutting in is much more than cutting out in the ceramics. Grinding damage of engineering ceramics could be forecasted and controlled by this simulation. So, grinding process could be optimized, and grinding efficiency and quality could be improved.

Cracks appear on the surface of the ceramics under the action of single diamond grain, the lead crack extends along the interior of the ceramic in the form of longitudinal cracks. In the lead crack propagation path, a small amount of oblique cracks will appear in other directions. The failure zone consists of tensile failure element and shear failure element. The shear failure is main failure form for the failure zone. When the grain stops, the crack ceases to expand into the interior of the ceramic, the crack failure elements in the zone are all shear failure elements. Because of the grinding and tensile failure of the grinding wheel, the crack extends along the arc and the wheel direction of rotation in the contact area between the wheel and the ceramic. When the penetration depth increases, the crack form is gradually transformed from the tensile failure element to the shear failure element. The number of broken parts in the cut is obviously more than that of the cutting part. The simulation results are basically consistent with the experimental results.

1. Introduction

Ceramic material has the characteristics of high hardness and great brittleness. But due to the grinding resistance, so that grinding ceramic parts will produce surface/sub-surface damage. Such as deformed layers, surface/sub-surface micro cracks, blurred surfaces, phase change regions, material powders, residual stresses, etc[1-3]. After the grinding damage is produced, the processed ceramic parts can ' t meet the application requirements. Especially, the surface/sub-surface cracks greatly reduce the strength of the part, so the research of crack damage has become an important work. Zhang Guangxiu is based on the indentation

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depth model of ceramic grinding surface crack and determine the parameters in the damage depth model[4].Yuan Dong discovered the origin, formation and expansion process of ceramic grinding cracks, and analyzed the characteristics of grinding cracks of Al2O3, ZrO2 and TiC-TiB2 composite ceramics[5,6]. Yang Xiao has researched the crack direction and established the model on the influence of the crack direction about the bending strength of the material[7]. The reason and extension mechanism of surface/subsurface crack and residual stress are analyzed, and the boundary element analysis method is proposed to research the crack by Kong Lingzhi[8]. Wu Xiaofeng has studied the mechanism of thermal shock cracking and the distribution of thermal shock crack in ceramic materials[9]. NieShijun used discrete element method to simulate the formation and propagation of cracks during the cutting process of ceramic materials, and proved that this method is effective[10]. Ni Jian introduced the mechanism, characteristics and measures to prevent the occurrence of cracks in the grinding process[11].

This paper is based on indentation fracture mechanics, and builds the mathematical model of damage depth of surface cracks in ceramic grinding. The UDEC simulation method was used to simulate the crack propagation in the silicon nitride ceramic material. The simulation results were compared and verified by plane single-stroke grinding experiment and surface crack damage observation.

2.The establishment of surface/subsurface crack damage depth model

Although the size of crack damage is large or small on the ceramic grinding surface/sub-surface, there is always a certain size in the depth direction. When the surface and sub surface materials bear the greater tensile stress, the crack easily extends and extends to the interior of the material[12,13]. According to the mechanics model of the indentation fracture, the grinding wheel is as a indenter and the damage depth model of the ceramic grinding surface crack is established.

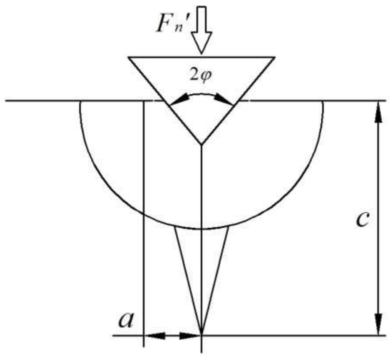


Figure 1 Crack propagation characteristics in the median

In Figure 1, the indenter with a cone angle of 2φ penetrates the surface of the material under the action of the load F_n', so that the latter produces a plastic indentation and produces a median crack with a characteristic size of *c*. Under the indentation load, a certain degree of plastic yield will occur around the plastic indentation, thus forming a plastic zone. This model is decomposed into two components, elastic components and residual components. The elastic field acts on the outside of the plastic zone, where the crack propagation actually takes place, the strength of this stress field and the external load at the same time to reach the fracture mechanics to build a damage maximum, and then was gradually reduced in the unloading process, until it is completely disappeared. The residual stress field is caused by the deformation mismatch at the elastic/plastic boundary, and its strength and the applied load reach the maximum value at the same time.

However, it has been maintained at the maximum since the end of the unloading process and the end of the indentation. Therefore, the stress intensity factor at the crack tip can be decomposed into the superposition of the residual stress intensity factor K_r and the elastic stress intensity factor K_e.

It is assumed that the residual stress intensity factor Kr is the main factor causing crack growth:

$$K_r = \beta E(\delta V / V)^{1/3}(\delta V)^{2/3} / c^{3/2} \quad (1)$$

In the formula: δ is the depth of the surface/sub-surface crack damage layer. β is a constant, it is determined by the shape of the indenter. δV is indentation volume. V is the plastic zone volume. c is median crack size.

$$\delta V / V \propto (H / E)^{3/2} \quad (2)$$

With the combination formula of (1) and (2), the residual stress intensity factor can be expressed as:

$$K_r = \beta (EH)^{1/2}(\delta V)^{2/3} / c^{3/2} \quad (3)$$

For stable crack growth, make fracture toughness Kc=Kr. The volume of the indentation formed by the regular indenter is defined by the characteristic angle φ.

$$\delta V = \alpha_1 a^3 \cot\varphi \quad (4)$$

In the formula: α_1 is indenter constant of geometric. a is indentation feature size. The approximate hardness is not constrained by the indentation shape, and the problem can be simplified. The hardness can be expressed as:

$$H = F_n' / (\alpha_0 a^2) \quad (5)$$

In the formula: α_0 is another indenter constant of geometric.F_n' is the normal force of a single indenter. Combined the formula (4) and (6) we can get:

$$\begin{cases} c = [\beta(\alpha_1 \cot\varphi)^{2/3} / \alpha_0]^{2/3}(E/H)^{1/3} k_c^{-2/3} F_n'^{2/3} \\ \eta = (E/H)^{1/3} k_c^{-2/3} \end{cases} \quad (6)$$

The normal force F_n' of a single indenter in the model is determined by the grinding force of the grinding wheel on the surface of the material to be grinded, η is the constants related to the characteristics of ceramic materials in the ceramic surface/subsurface crack damage model. Thus, the damage depth model of ceramic grinding surface/subsurface crack shows the influence of ceramic properties and grinding conditions on the surface/subsurface damage depth of ceramic grinding.

3.Numerical simulation of single abrasive indentation by UDEC

3.1. Simulation modeling

In order to analyze the expansion of indentation cracks on the surface of silicon nitride ceramics, a series of two-dimensional planar equivalent model was established by using two-dimensional general discrete element software UDEC (Universal Distinct Element Code). The physical model is mainly accomplished by the generation of blocks and joints, simulation of boundary conditions, and the simulation of the motion process is mainly by the application of load and velocity [14-16]. The ceramic block and the grinding wheel block are defined as deformable bodies. The initial separation state between deformable bodies is achieved by the CELL command. The material parameters are assigned to the deformable body (the physical and mechanical properties of ceramic and diamond grains can be found in the Table 1).

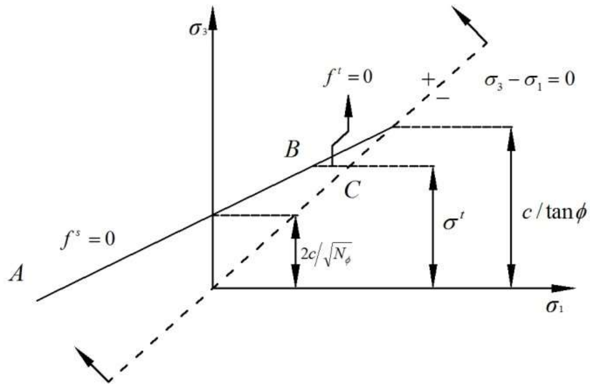


Fig. 2 - The Mohr-Coulomb failure criterions in UDEC software.

The surface of silicon nitride ceramics is pressed by single diamond grain under 300N force and the process of cracks growth is shown as Fig. 3. Comparing the six figures we can see that cracks appear on the surface of the ceramics under the action of one grain, and the cracks extend to the deep of the ceramics as the penetration depth of the grain increases. The failure zone consists of tensile failure element and shear failure element. The shear failure is main failure form for the failure zone. When the grain stops, the crack ceases to expand into the interior of the ceramic, the crack failure elements in the zone are all shear failure elements.

Table 1

Physical properties of grinding wheels and workpieces[17]

Material	Density/ kg•m^{-3}	Hardness/ kg•mm^{-1}	Bending strength/ MPa	Compressive strength/ MPa	Fracture toughness/ MPa•m$^{-3/2}$	Elastic Modulus/ GPa	Poisson's ratio
Silicon nitride	3150	1700-2700	900	3500	7	320	0.26
Diamond	3515	8600-11000	885	3000-4380	4-5	105	0.2

The modified Mohr-Coulomb criterion in UDEC was used in the model as shown in Fig. 2. In the formula, the fs represent the Mohr-Coulomb yield criterion:

$$f^s=\sigma_1-\sigma_3N_\phi+2b\sqrt{N_\phi} \quad (7)$$

In the formula: σ1 is the first principal stress. σ3 is the third principal stress. b is cohesion. ϕ is the friction angle.

$$N_\phi=\frac{1+\sin\phi}{1-\sin\phi} \quad (8)$$

f^t is tension yield criterion:

$$f^t=\sigma^t-\sigma_3 \quad (9)$$

In the formula: σ^t is tensile strength.

The displacement between the left and right sides of the silicon nitride ceramic block and the bottom boundary is restrained. The 300N normal thrust force is applied on the unit node of the diamond wheels block, and the 5m/s speed of the normal propulsion is applied at the same time.

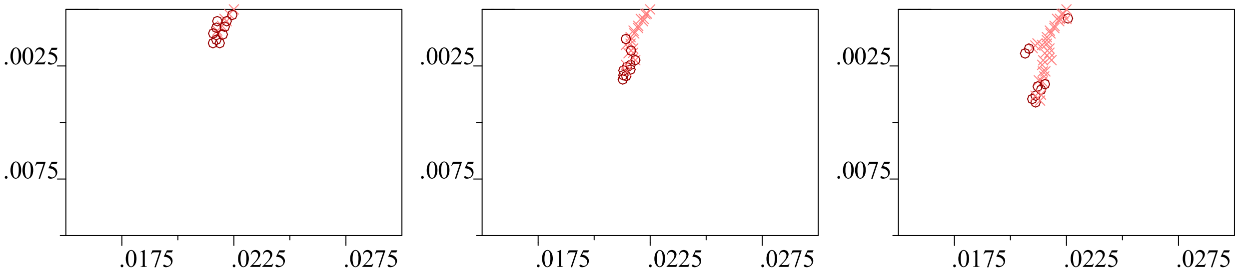
3.2. The simulation results and analysis

1. Analysis on the process of cracks growth of silicon nitride ceramics by single diamond grain.

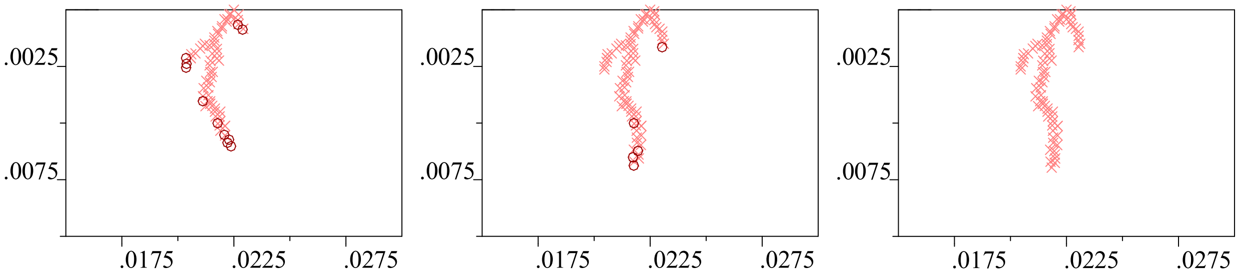
From the simulation results we can see that the direction of crack extending is irregular, and the lead crack extends along the interior of the ceramic in the form of longitudinal cracks. In the lead crack propagation path, a small amount of oblique cracks will appear in other directions. With the increase of penetration depth, the lead crack continues to extend inside the ceramic until the ceramic chip breaks. From Fig. 3(f) we can see that the maximum depth of crack extending inside silicon nitride ceramics under 300N diamond grain is about 7.5 μm.

2. Analysis of pressing process of diamond wheel

Fig. 4 is the analysis of the crack extending during the process of grinding the silicon nitride ceramic on the condition that the diamond grinding wheel has a speed of 50m/s and a vertical pressing rate of 1000mm/min. Comparing the simulation results of Fig. 4 (a)-(f) can be known, the amount of cracks of silicon nitride ceramics increase gradually with the penetration depth of grinding wheel increasing. In contrast to the different cracks extending in Fig. 4, it is found that when the penetration depth increases, the crack form is gradually transformed from the tensile failure element to the shear failure element.

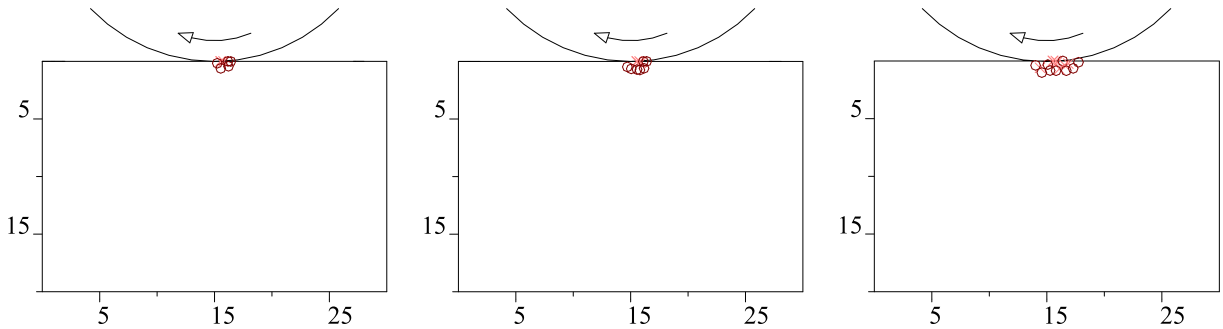


(a)step50(b)step100(c)step200

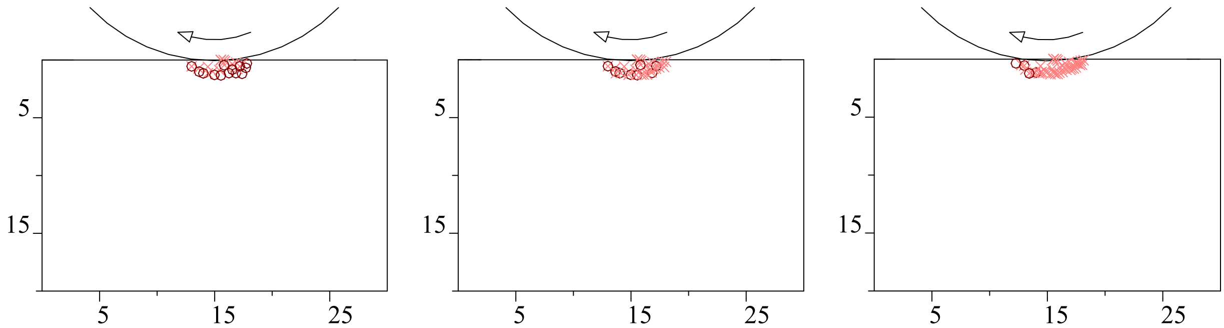


(d)step300(e)step400(f)step500

Fig. 3 - The crack extending in silicon nitride ceramics under the action of single diamond grain



(a)step50(b)step100(c)step200



(d)step300(e)step400(f)step500

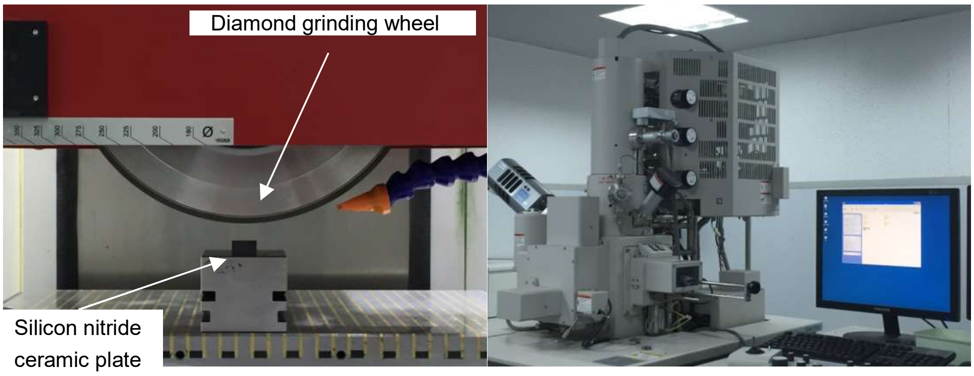
Fig. 4 - The crack extending of silicon nitride ceramics under the action of diamond grinding wheel

From the six pictures it can be seen that, when the grinding wheel cuts into the ceramic surface, the number of broken parts in the cut is obviously more than that of the cutting part. Because of the grinding and tensile failure of the grinding wheel, the crack extends along the arc and the wheel direction of rotation in the contact area between the wheel and the ceramic. It can be seen from Fig. 4 (f), when the grinding depth is 50μm, the crack breaks the ceramic along a circular arc in the contact part between the surface and grinding wheel. The depth and width of arc crack are about 2mm and 8mm.

4. Experimental results and analysis

4.1. Experimental equipment and testing instruments

The experimental equipment is BLOHM Orbit 36 CNC manufactured by United Grinding, the maximum grinding speed of diamond grinding wheel is up to 70m/s. The equipment and tooling is shown as Fig. 5 (a). The surface cracks extending in silicon nitride ceramics workpiece after machining is observed by Field Emission Scanning Electron Microscope of S-4800 shown as Fig. 5 (b).



(a) BLOHM Orbit 36 CNC(b) Field emission scanning electron microscope of S-4800

Fig. 5- The experimental equipments and testing instruments.

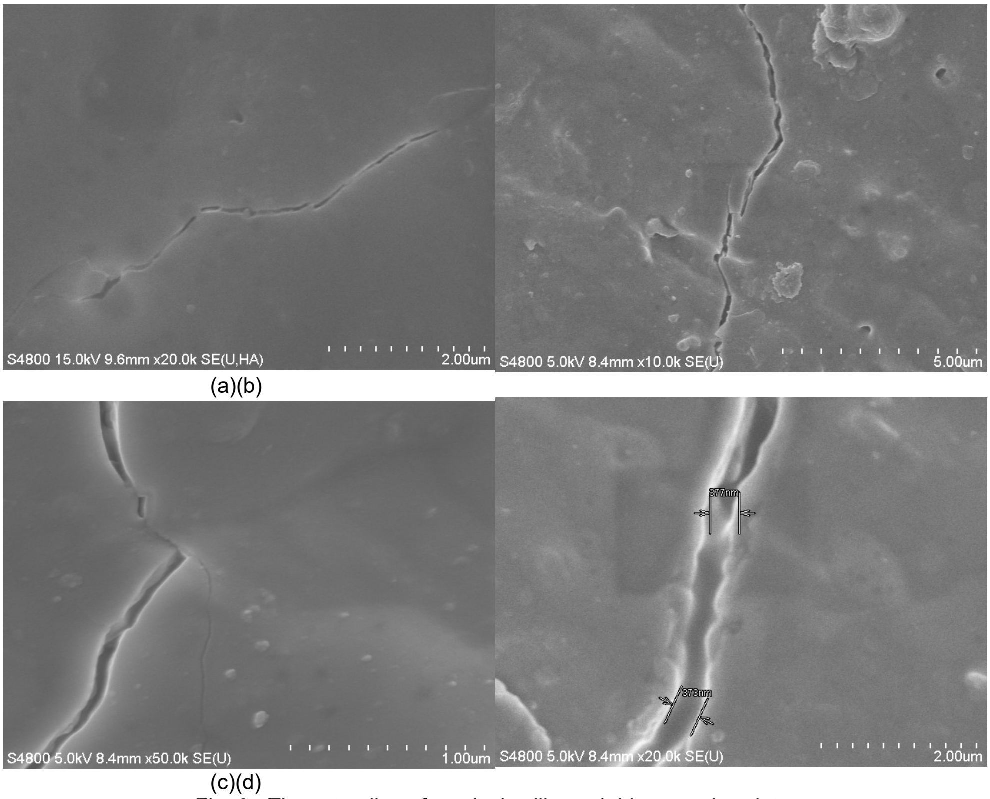


Fig. 6 - The extending of cracks in silicon nitride ceramics plate.

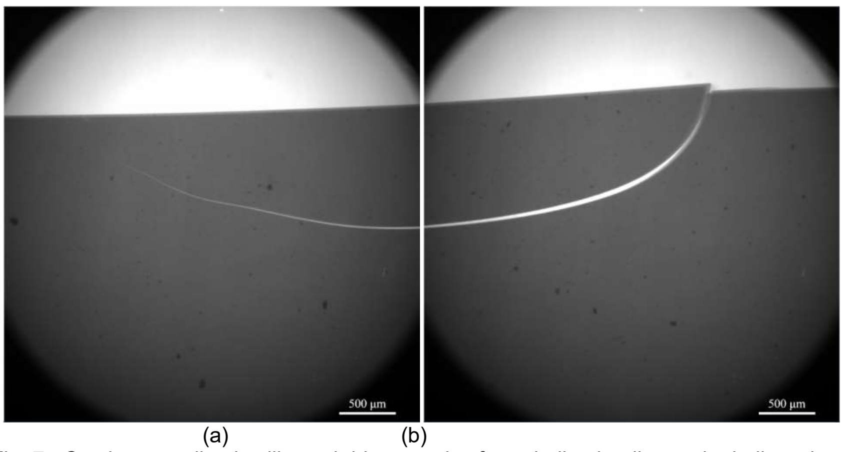


Fig. 7 - Cracks extending in silicon nitride ceramic after grinding by diamond grinding wheel.

4.2 Experimental results and analysis

The cracks extending in silicon nitride ceramic plate under single diamond grain is shown as Fig. 6. Comparing the experimental results from Fig. 6 (a)-(d) we can see that the cracks occur in the silicon nitride ceramics under the pressure of diamond grain block, and the crack extending direction is irregular. In the course of the crack formation, it is expanded only in the form of a lead crack. In the lead crack propagation path, a small amount of oblique cracks will appear in other directions and this is basically consistent with the simulation results. From the experimental results, the width of crack is about 0.37 μm.

Fig. 7 shows the cracks extending of silicon nitride ceramic in the grinding process of diamond wheel with linear speed of 50m/s and vertical pressing rate of 1000mm/min. From the experiment results can be seen, under the action of wheel grinding and tensile failure the crack extends along nitride ceramic plate contacting with the grinding wheel get dropped. The extending of cracks in cut part is more obvious than the cutting part. So, the arc and the wheel direction of rotation in the contact area between the wheel and the ceramic. With the increase of grinding depth, the circular arc crack extends along the contact surface between the ceramic and the grinding wheel from the cut point to the cutting part. Then it makes the silicon
simulation results are basically consistent with the experimental results

5.Conclusion

Cracks appear on the surface of the ceramics under the action of single diamond grain, the lead crack extends along the interior of the ceramic in the form of longitudinal cracks. In the lead crack propagation path, a small amount of oblique cracks will appear in other directions. The failure zone consists of tensile failure element and shear failure element. The shear failure is main failure form for the failure zone. When the grain stops, the crack ceases to expand into the interior of the ceramic, the crack failure elements in the zone are all shear failure elements. Because of the grinding and tensile failure of the grinding wheel, the crack extends along the arc and the wheel direction of rotation in the contact area between the wheel and the ceramic. When the penetration depth increases, the crack form is gradually transformed from the tensile failure element to the shear failure element. The number of broken parts in the cut is obviously more than that of the cutting part. The simulation results are basically consistent with the experimental results.

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