Investigation on the Effect of Dynamic Fracture Toughness to Zirconia Ceramic Grinding Performance with Different Grain Sizes

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Research Article

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Investigation on the Effect of Dynamic Fracture Toughness to Zirconia Ceramic Grinding Performance with Different Grain Sizes

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Abstract

To reveal the material removal mechanism of zirconia ceramics, an improved prediction models of the critical grinding force and maximum subsurface damage depth models are developed based on the dynamic fracture toughness. The effects of three different grain sizes on the material removal mechanism during brittle- ductile transition process of zirconia ceramics is analyzed through grinding experiments. And the influence of grain size on grinding force, workpiece surface roughness, surface fragmentation rate and subsurface damage depth in grinding are discussed. The results of the experiment results indicated that the value of dynamic fracture toughness tends to decrease with an increase in equivalent grinding thickness, and the ductile removal range of zirconia ceramics expands for the reason that the critical grinding force considering dynamic fracture toughness is higher than the static grinding force considering static fracture toughness, and the maximum subsurface damage depth is closer to actual maximum subsurface damage depth. Besides the smaller the grain size of zirconia ceramics, the higher the surface quality of grinding.

Keywords Zirconia ceramic · Grain size · Dynamic fracture toughness · Critical grinding force · Maximum subsurface damage depth

1 Introduction[1]

Engineering ceramics have the advantages of high strength, high hardness, low density, good wear resistance, good heat insulation performance, and good chemical stability. They are widely used in aerospace, petrochemical, automobile manufacturing and other industries [1]. The zirconia (ZrO_2) ceramics in engineering ceramics have attracted much attention because of their good toughness and ability to overcome the inherent brittleness of engineering ceramic materials. They have become important raw materials for refractory materials, high-temperature structural materials and electronic materials. However, during the grinding process, the surface/subsurface of ZrO_2 ceramics is prone to damages such as micro-cracks, and the damage of the processed surface is difficult to measure and control, resulting in a decrease in the life of parts [2-4] Therefore, it is of great significance to study the material removal behavior of ZrO_2 ceramics and predict the degree of subsurface damage in order to improve the processing efficiency and optimize the processing quality.

The material removal mechanism of engineering ceramics is mainly concentrated in two aspects: On the one hand, the critical cutting depth of brittle-ductile transition of single grit is calculated according to the theory of indentation fracture mechanics, and verified by numerical simulation and scratch experiment [5-8]. On the other hand, it explores the change law between grinding performance and grinding process parameters such as grinding force, grinding specific energy, chip morphology and surface morphology during the grinding process [9-13], so as to find the critical depth of cut for brittle-ductile transition. However, only based on the morphology of the chips and the surface morphology of the workpiece cannot fully reveal the nature of the brittle-plastic transition of the material. Zhang et al. [14-16] argued that the generation of subsurface microcracks cannot be ignored in the processing of hard and brittle materials. Subsurface damage is an important basis for judging the material removal mode in the processing of hard and brittle materials. In recent years, the subsurface damage has been widely concerned by some scholars. Yang et al. [17] proposed a new theoretical stress field model based on the relationship between the strain rate and material properties which can evaluate the median crack length and

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determine the dimension of the subsurface damage layer. Wang et al. [18] analyzed the effects of wheel speed, grinding depth and abrasive tip angle on the subsurface damage of brittle materials in grinding, and the effect of grinding depth on subsurface damage was weaker than that of wheel speed. Meng et al. [19] studied the removal mechanism of silicon carbide in the nanoscale grinding process and proposed that the depth of the residual dislocation line determines the depth of the surface damage layer.

In the process of studying the material removal mechanism, it is found that the fracture toughness of engineering ceramics is an important mechanical property that affects its grinding performance. When the theory of indentation fracture mechanics is used to analyze the brittle plastic transformation of materials, a constant value is often used to calculate the fracture toughness in the formula of critical cutting depth. However, the static fracture toughness under impact load cannot accurately reflect the generation and propagation mechanism of dynamic cracks [20-24], in order to improve the grinding performance of engineering ceramics, studies on dynamic fracture toughness are increasing. Xie et al. [25] proposed that the cutting deformation force of ceramic materials was related to the material removal method, mechanical properties and grinding parameters. When brittle fracture was removed, the higher the fracture toughness and the lower the microhardness were, the greater the cutting deformation force was. Kalthoff et al. [26] presented that the dynamic fracture toughness can be obtained by establishing the relationship between the impact response curve and the measured time. Chen et al. [18] used dynamic fracture toughness instead of static fracture toughness and dynamic impact load instead of static load, which is more in line with the actual grinding process. Yang et al. [27,28] established a prediction model of minimum chip thickness and ductility-brittle transition chip thickness based on the grinding mechanism, in which the dynamic fracture toughness of brittle materials is approximately 30% of the static fracture toughness. Liu et al. [29] combined the Johnson-Holmquist 2 damage model of brittle materials with Griffith fracture theory to establish the dynamic fracture toughness model. It is concluded that increasing the linear speed of the grinding wheel can improve the fracture toughness and increase the lateral crack of the workpiece, reduce the radial crack of the workpiece and reduce the grinding force. Wu et al. [30,31] developed the critical ductile-brittle transition model based on the dynamic fracture toughness model which considering wheel speed and chip thickness, and investigated that ductile grinding can be obtained by combining higher grinding speed with smaller chip thickness. Compared with traditional grinding, higher grinding speed can infinitely improve the critical chip thickness of silicon carbide ductile grinding. Li et al. [32] analyzed that the increase of strain rate leads to higher fracture toughness, and indicated that brittle materials have the tendency of ductility under impact mechanical load. It is believed that the speed effect of high-speed grinding will change the contact behavior between brittle materials and abrasive particles.

When studying the grinding performance of engineering ceramics, the grain size of grinding wheel cannot be ignored. Yang et al. [33] investigated that the cutting force decreased with the increase of grain size, and believed that the grain boundary hindered the movement of dislocation, thereby improving the strength of the material. Demir et al. [34] investigated the effects of grain size on workpiece surface roughness and grinding force, and concluded that as the particle size of the grinding wheel increases, the surface roughness value increases and the grinding force increases. Kannappan et al. [35] studied the effects of grain size and operating parameters on the mechanics of grinding, and found that the finer the particle size, the larger the wear surface area, and the greater the energy input per unit grinding area, but the smaller the g ratio and the life of the grinding wheel tool. However, the factors affecting the performance of engineering ceramics are often ignored in the grinding process. The difference in grain size makes ceramics have great differences in microstructure, which leads to changes in the mechanical properties of the materials.

It can be seen from the above research that the process parameters in the grinding process of engineering ceramics have a significant impact on the mechanical properties of its materials, and the mechanical properties of the materials affect the quality of the grinding process. Through the above analysis, previous studies have focused on the dynamic fracture toughness which has a marked impact on the brittle-ductile transformation process of engineering ceramics. Based on dynamic fracture toughness, numerous models of grinding force and subsurface damage depth have been established, but there are few studies on how process parameters affect dynamic fracture toughness. Therefore, in combination with the dynamic mechanical properties of materials, the influence of process parameters on the grinding performance of engineering ceramics needs to be further studied and explored. Hence, in this paper, the grinding of ZrO_2 ceramic with different grain sizes is taken as the research object. On the basis of considering the influence of dynamic fracture toughness, the dynamic critical grinding force and dynamic critical subsurface damage depth models that generate grinding cracks (lateral and median cracks) are established, and verified by plane grinding process experiments. The effects of grinding process parameters on critical grinding force and subsurface damage depth under different grain sizes were analyzed, and the effects of grain size on grinding force, surface roughness, surface cracking rate and subsurface damage of ZrO_2 ceramic were discussed to better reveal the material removal mechanism of ZrO_2 ceramic grinding.

2. Research methodology

2.1 Experimental setup and grinding parameters

The grinding experiments of ZrO_2 ceramic was carried out on high precision horizontal surface grinder (MGK7120×6/F) equipped with resin bond grinding wheel (brand SDC100N100B, circumferential diameter 200mm). The grains used in the process were diamond, whose mesh were 100/120#. Since this experiment is mainly to study the influence of grain size and dynamic fracture toughness of ZrO_2 ceramic material on its grinding performance, in order to avoid the influence of grinding fluid on the grinding quality, the dry grinding method is adopted. The grinding experimental setup is shown in Fig. 1. The dynamometer (Kistler 9253B) was employed to measure the grinding force, the surface morphologies of the workpiece were observed by super depth of field microscope (VHX-500FE), the surface roughness was measured by roughness measuring instrument (MarSurf M300). With the purpose of detecting material subsurface damage depth in the experiments, scanning electron microscope (JSM-6360LV) has been used to obtain more pictures of subsurface damage. Each set of data was obtained from 10 measurements.

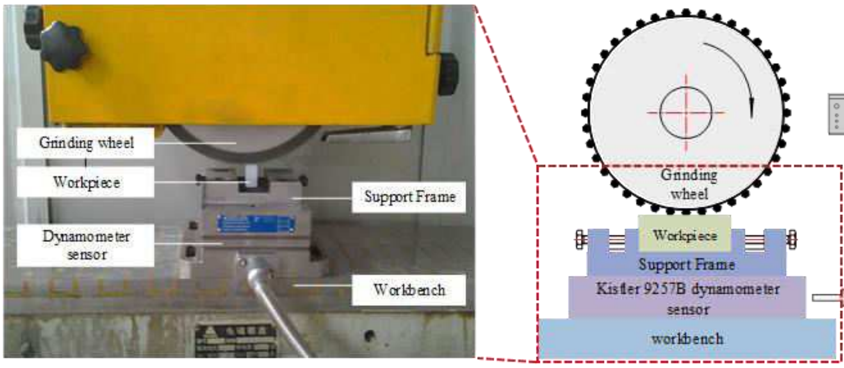


Fig. 1 Grinding experimental setup diagram

Table 1 Related parameters of grinding experiment

Parameters	Value
Grinding speed v_s [m/s]	9.4,12.6,15.7,18.8
Grinding infeed speed v_w [mm/s]	20,25,30,35
Grinding depth a_p [μm]	2,5,10,15

The material of workpiece was ZrO_2 ceramic with the size of 10mm(length) ×20mm(width)×20mm (height). The grain sizes of workpiece are respectively 50nm, 500nm, 5000nm, and the orthogonal experiment is adopted. The experimental parameters and levels are shown in Table 1. The three grain sizes are all subjected to plane grinding experiments according to the 16 experimental schemes designed in Table 1.

2.2 Dynamic critical grinding force model of single grit with cracks (lateral crack, median crack)

Based on indentation fracture mechanics, the crack generates and expands if the grinding force of single grit is greater than the critical load of the crack in the grinding process, and the material removal method is judged as brittle removal. Considering the influence of actual grinding conditions, the critical load P_l^* [36] for generating lateral cracks and the critical load P^* for generating median / radial cracks can be expressed as [37]:

$$P_l^* = 2\times10^5 C(\frac{K_{IC}{}^4}{H_v{}^3}) \tag{1}$$

$$P^* = 54.5(\frac{\alpha}{\eta^2\gamma^4})(\frac{K_{IC}{}^4}{H_v{}^3}) \tag{2}$$

Where, K_{IC} is the static fracture toughness of ceramic material, H_v is the hardness of the material, and C is the coefficient obtained considering the actual grinding conditions. According to the experiment, C=0.56 [38], α、η、γ are dimensionless constant, which can be obtained through the measurement and for typical Vickers hardness indenter, $\alpha = 2/\pi, \eta \approx 1, \gamma \approx 0.2$.

It can be seen from Eq. (1) and Eq. (2) that the critical load of the material is not only related to the static fracture toughness, but also related to the hardness during the grinding process of ceramic material. Moreover, it shows that the critical load increases with static fracture toughness and decreases with hardness. When the normal grinding force of single grit is less than the critical load, the lateral crack does not appear and the material removal method is ductile removed; On the contrary if the normal grinding force is greater than the critical load, the lateral crack generates and expands, and brittle removed occurs on the ceramic material.

Eq. (1) and Eq. (2) are calculated based on the static fracture toughness of ceramic materials, but the fracture toughness of ceramic materials varies in actual grinding process, that's why the calculation results are inaccurate. For that reason, it needs to considering the dynamic fracture toughness K_{ID} [2] to describe the critical load, which is described as follows:

$$K_{ID} = (m + n\ln\dot{\varepsilon})K_{IC} \tag{3}$$

where $\dot{\varepsilon}$ is the strain rate, m and n are material constants and the value of them are determined by actual experiment. Consequently, the new dynamic normal critical grinding force model for a single grit with lateral crack F_n and the new critical load model for median / radial cracks of ZrO_2 ceramic grinding can be described as following:

$$F_n = 1.12\times10^5(\frac{K_{ID}{}^4}{H_v{}^3}) \tag{4}$$

$$F_t = 2.2\times10^4(\frac{K_{ID}{}^4}{H_v{}^3}) \tag{5}$$

2.3 Dynamic maximum grinding subsurface damage depth

In the grinding process of ZrO_2 ceramic, when the actual grinding force of single grit is greater than the critical grinding force for radial cracks, damage will be produced to the surface and subsurface of the workpiece, which will seriously affect the performance and life of the workpiece.

In order to predict the grinding subsurface damage depth, the dynamic maximum grinding subsurface damage depth model of ZrO_2 ceramic was established. Combined with Reference [39] and the dynamic load characteristics of the actual grinding process, the dynamic maximum grinding subsurface damage depth δ_{md} of ZrO_2 ceramic is obtained as follows:

$$\delta_{md} = (\frac{4\pi}{r_g})^{-4/9} x^{2/3} (\frac{K_{ID}}{\sqrt{E}} H_v{}^{5/6})^{-2/3} f_{gn}{}^{8/9} \tag{6}$$

Where, x is a constant, r_g is the abrasive radius, E is the elastic modulus of the material, and f_{gn} is the grinding force of single grit.

It can be seen from Eq. (6) that the maximum grinding subsurface damage depth decreases with the increase of dynamic fracture toughness of ZrO_2 ceramic.

3. Results and discussion

3.1 The dynamic fracture toughness of ZrO_2 ceramic

In order to calculate the dynamic fracture toughness of ZrO_2 ceramic with three grain sizes, the elastic compression experiment was carried out to measure the static compression strength and elastic modulus, and the hardness indentation experiment was conducted to obtain the hardness and static fracture toughness of ZrO_2 ceramic. The specific experimental data are shown in Table 2. According to the mechanical properties in Table 2, the dynamic fracture toughness of ZrO_2 ceramics is obtained by grinding process parameters of sixteen orthogonal experiments, as shown in Fig. 2(a). Comparing the static fracture toughness in Table 2 with the dynamic fracture toughness in Fig. 2(a) in the grinding process, it can be seen that the static fracture toughness is significantly smaller than the dynamic fracture toughness, the strain rate strengthening effect is the main reason for the phenomenon.

Table 2 Relevant mechanical properties of ZrO_2 ceramic

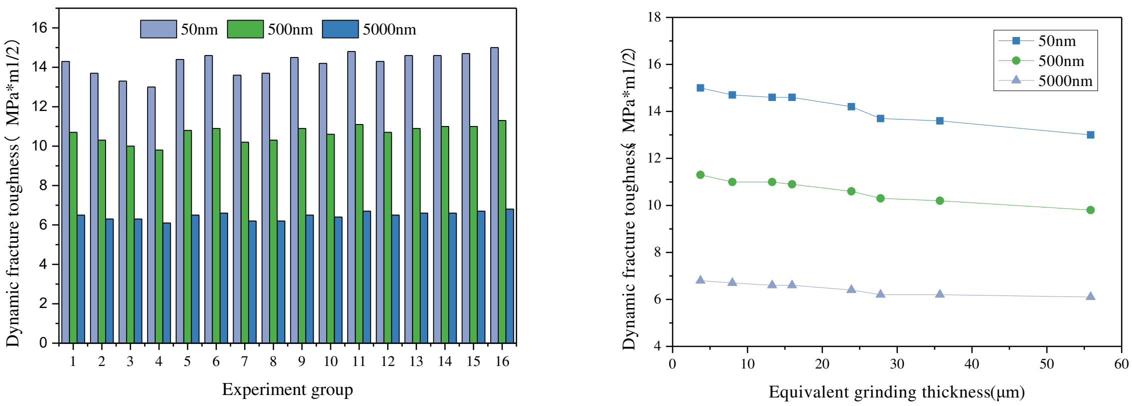
Grain size （nm）	E （Gpa）	H_v （H_v30）	K_{IC} (MPa×m$^{1/2}$)	m	n
50	181	1364	6.14	-7.6	1.34
500	207	1150	5.75	-4.4	0.85
5000	230	849	5.56	-2.84	0.54

In order to analyze the influence of machining parameters on the dynamic fracture toughness, equivalent grinding thickness a_{eq} is introduced. Equivalent grinding thickness refers to the thickness of a hypothetical cross-sectional area formed by the cross-sectional areas of the chips at the same time participating in the work within the contact length range of the unit width of the grinding wheel, and it can be expressed as:

$$a_{eq} = \frac{v_w}{v_s} a_p \tag{7}$$

It can be seen from Fig. 2(b) that the dynamic fracture toughness is not only related to the equivalent grinding thickness, but also related to the grain size of the material. Under the same conditions, the dynamic fracture toughness is decreased nonlinearly with the equivalent grinding thickness. This is the reason that the equivalent grinding thickness is determined by processing parameters, and the strain rate is changed by the different processing parameters. In addition, ZrO_2 ceramic is a strain rate strengthening material, which the dynamic fracture toughness is determined by the strain rate.

On the other hand, it can be concluded from Fig. 2 that the dynamic fracture toughness is increased with the decrease of ZrO_2 ceramic grain size. It is main reason that the finer the grain is, resulting in larger the grain boundary area and more tortuous the grain boundary, causing more unfavorable to the crack propagation. Moreover, the better the grain coordination is, the less the large defects and voids are. More energy can be absorbed during the fracture process, and the higher toughness is showed by ZrO_2 ceramics.



(a) (b)

Fig. 2 Effect of different parameters on the dynamic fracture toughness (**a**) Effect of equivalent grinding thickness on dynamic fracture toughness (**b**)

3.2 Comparison of static and dynamic critical grinding forces of ZrO_2 ceramic

In order to verify the accuracy of the model, it is necessary to analyze the critical grinding force of brittle ductile transition in the grinding experiment of ZrO_2 ceramic under three grain sizes. And according to the previous analysis, Bifano [40] proposed that the material removal of brittle materials is defined as ductile removal under the condition that the relative area ratio of surface damage less than 10%. Zhang [2] pointed out that attention should be given to subsurface damage in the material removal mechanism analysis for brittle materials. Therefore, the material removal mechanism can be investigated by analyzing the surface cracking rate and subsurface damage depth after grinding. The grinding experiments with grain sizes of 50nm, 500nm and 5000nm were carried out, and the grinding force, the surface cracking rate and subsurface damage were detected in this paper.

Table 3 and Table 4 are the static and dynamic critical grinding forces for brittle-ductile transition when lateral cracks and median cracks are generated in the 1st group of process parameters, respectively. It can be apparently seen that dynamic critical grinding forces is difference from static critical grinding forces for the brittle-ductile transition of ZrO_2 ceramics under three grain sizes. Comparing Table 3 and Table 4, the material removal was brittle removal according to the static critical grinding force model, while the material removal was ductile removal using the dynamic critical grinding force model.

Table 3 Comparison of static and dynamic critical grinding forces of single grit with lateral cracks in the 1st group (v_s =9.4m/s, v_w=20mm/s, a_p=2μm)

Grain size	Static critical grinding force(N)	Dynamic critical grinding force (N)	Actual grinding force(N)
50	5.24×10^{-5}	2.06×10^{-3}	3.44×10^{-4}
500	6.06×10^{-5}	9.67×10^{-4}	8.92×10^{-5}
5000	1.42×10^{-4}	3.27×10^{-4}	3.05×10^{-5}

Table 4 Comparison of static and dynamic critical grinding forces of single grit with median cracks in the 1st group (v_s=9.4m/s, v_w=20mm/s,a_p=2μm)

Grain size	Static critical grinding force(N)	Dynamic critical grinding force(N)	Actual grinding force(N)
50	1.03×10^{-5}	4.05×10^{-4}	3.44×10^{-4}
500	1.19×10^{-5}	1.90×10^{-4}	8.92×10^{-5}
5000	2.79×10^{-5}	6.42×10^{-5}	3.05×10^{-5}

The surface morphology and the subsurface damage diagram of ZrO_2 ceramic with three grain sizes under the 1^{st} group of grinding process parameters were shown in Fig.3 and Fig.4 separately. The material removal mechanism in the actual grinding process was analyzed. It can be seen from Fig. 3 that material surface is dominated by plastic scratches, and the surface cracking rate is less than 10 %. Moreover, as shown in Fig. 4, it can be seen that no crack appeared on the subsurface. It indicates that the material removal mechanism should be ductile removal. On the other hand, by analyzing the calculated values and the experimental results in Table 4 and Table 5, it is obtained that the actual grinding force of single grit is smaller than the critical dynamic grinding force generated by lateral / median cracks. Therefore, it is verified that the critical grinding force model based on dynamic fracture toughness is more effective than the static critical grinding force model for brittle-ductile transition.

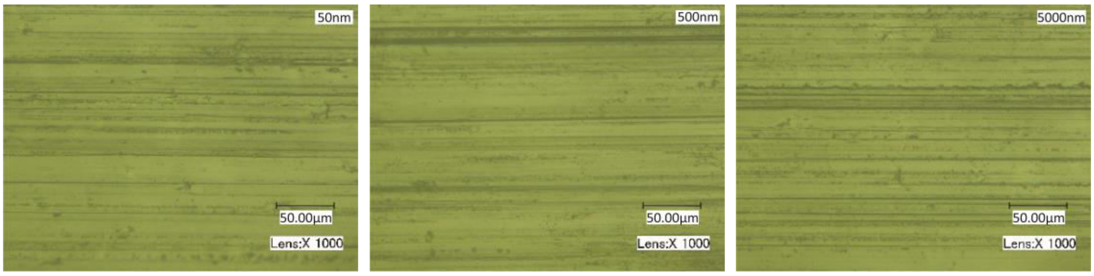


Fig. 3 Surface topography of the workpiece in the 1^{st} group(v_s =9.4m/s, v_w=20mm/s, a_p=2µm)

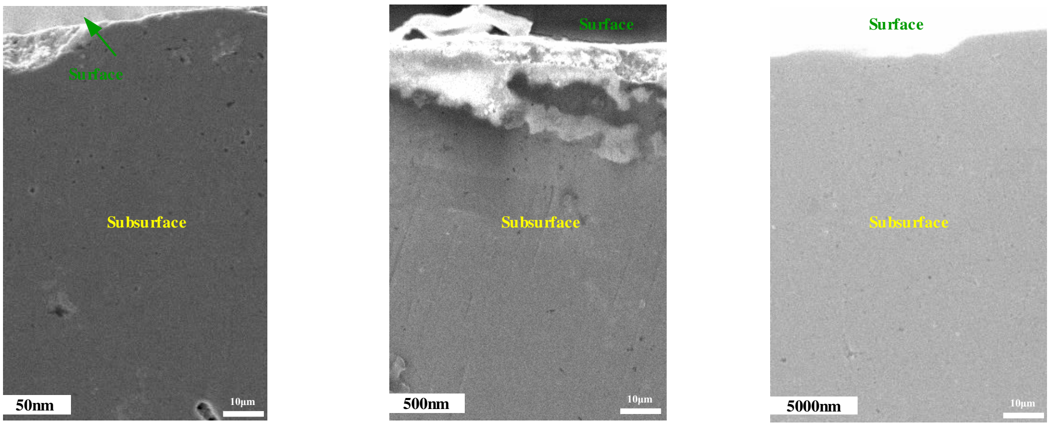


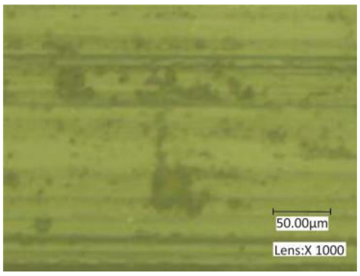
Fig. 4 The subsurface damage of the workpiece in the 1st group(v_s =9.4m/s, v_w=20mm/s, a_p=2µm)

Table 5 Dynamic critical grinding forces of single grit with lateral cracks under different grinding parameters

Grain size (nm)	The 5^{th} group		The 9^{th} group		The 13^{th} group	
	critical grinding force(N)	actual grinding force(N)	critical grinding force(N)	actual grinding force(N)	critical grinding force(N)	actual grinding force(N)
50	2.12×10^{-3}	0.17	2.18×10^{-3}	0.36	2.24×10^{-3}	0.47
500	1.00×10^{-3}	0.09	1.03×10^{-3}	0.30	2.03×10^{-3}	0.43
5000	3.27×10^{-4}	0.05	3.27×10^{-4}	0.14	3.47×10^{-4}	0.30

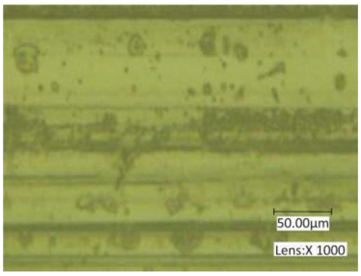
To further validate the accuracy of the model, the dynamic critical grinding force and the actual grinding force under the grinding process parameters of the 5^{th} group, the 9^{th} group and the 13^{th} group are compared. The comparison results are shown in Table 5. It can be seen from Table 5 that the actual grinding force on single grit is over than the critical grinding force for lateral cracks. It can be concluded that the material removal is brittle removal.

For ZrO_2 ceramics with grain size of 500 nm, the surface morphology under grinding parameters of the 5th group, the 9th group and the 13th group are shown in Fig.5. It can be concluded that the surface cracking rate is 13.7%, 18.4% and 34.27% in the order of the three grinding process parameters mentioned above, and their values are more than 10%. Hence, the material removal is brittle removal, and the surface cracking rate increases with increasing grinding depth. Furthermore, the validity of the dynamic critical grinding force model to determine the material removal method is verified.



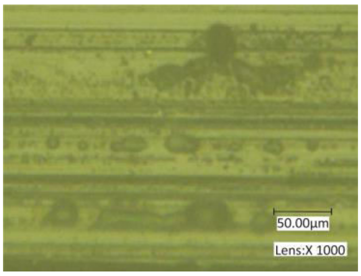
(v_s=12.6m/s, v_w=20mm/s, a_p=5μm)

(a) the 5th group



(v_s =15.7m/s, v_w=20mm/s, a_p=10μm)

(b) the 9th group



(v_s =18.8m/s, v_w=20mm/s, a_p=15μm)

(c) the 13th group

Fig. 5 Surface topography of 500nm ZrO_2 ceramic under different grinding process parameters

3.3 Influence of grinding process parameters on subsurface damage depth

According to Table 5 and the dynamic critical grinding force model, the result indicate that material removal was ductile removal without surface lateral cracks under the grinding process parameters of the 1st group. Similarly, it can be seen from the model that material removal was brittle removal and lateral cracks were generated under the grinding process parameters of the 5th group, the 9th group and the 13th group.

In order to calculate the subsurface damage depth, a dynamic maximum subsurface damage depth model for ZrO_2 ceramic was established that expressed as Eq. (6). The static maximum subsurface damage depth and dynamic maximum subsurface damage depth of ZrO_2 ceramic with three grain sizes under the 13th group of grinding process parameters were calculated, and the actual maximum subsurface damage depth was measured by SEM. The comparison results are shown in Fig. 6.

Fig. 6 depicts the dynamic maximum subsurface damage depth of 60.2μm for ZrO2 ceramics with grain size of 50 nm, which is close to the actual maximum subsurface damage depth of 52μm, while the static maximum subsurface damage depth of 113μm that much larger than the actual maximum subsurface damage depth, under the 13th set of grinding process parameters. Therefore, the dynamic maximum subsurface damage depth model is closer to the actual subsurface damage depth than the static model, and the prediction results are more accurate.

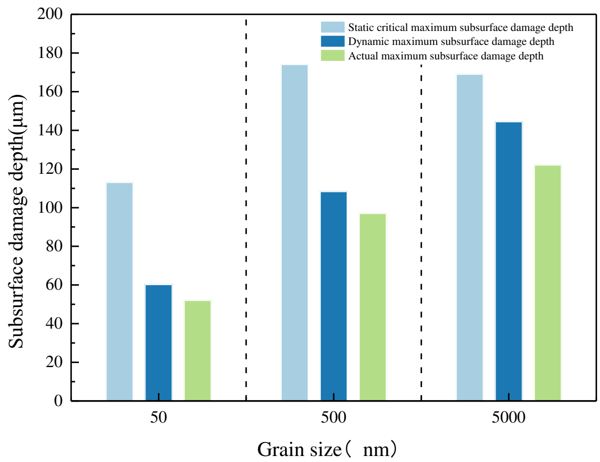


Fig. 6 The maximum subsurface damage depth under the 13th group (v_s =18.8m/s, v_w=20mm/s, a_p=15μm).

Fig. 7 illustrates that the subsurface damage of ZrO2 ceramic with three grain sizes respectively obtained by SEM under the 13th group of grinding process parameters. It is demonstrated that part of the subsurface damage is not connected to the grinding surface for the reason that the crack propagation is not perpendicular to the grinding surface. If 45° oblique throwing is adopted, the subsurface damage can be more obvious.

For ZrO_2 ceramics with grain size of 500 nm, the subsurface damage diagram under the 1st group, the 5th group and the 13th group are shown in Fig.8. Combined with Table 4 and Fig. 8a, it can be seen that the actual grinding force of single grit under the 1st group is less than the critical grinding force, and the material removal is ductile removal without subsurface damage. The grinding force of single grit under the 5th group is greater than the critical grinding force, and the material removal method is brittle removed, and it can be clearly observed from Fig. 8b that median cracks and lateral cracks appeared on the subsurface of the workpiece and the maximum subsurface damage depth is 31μm. Besides, the grinding force of single grit under the 13th group is greater than the critical grinding force, and the material removal is brittle removal. Fig. 8c shows that many cracks arose on the subsurface of the workpiece and lateral cracks occurred, and the maximum subsurface damage depth is 97μm that deeper than under the 5th group with 31μm. It is indicated that the level of subsurface damage of workpiece can be analyzed according to the grinding force in the grinding process.

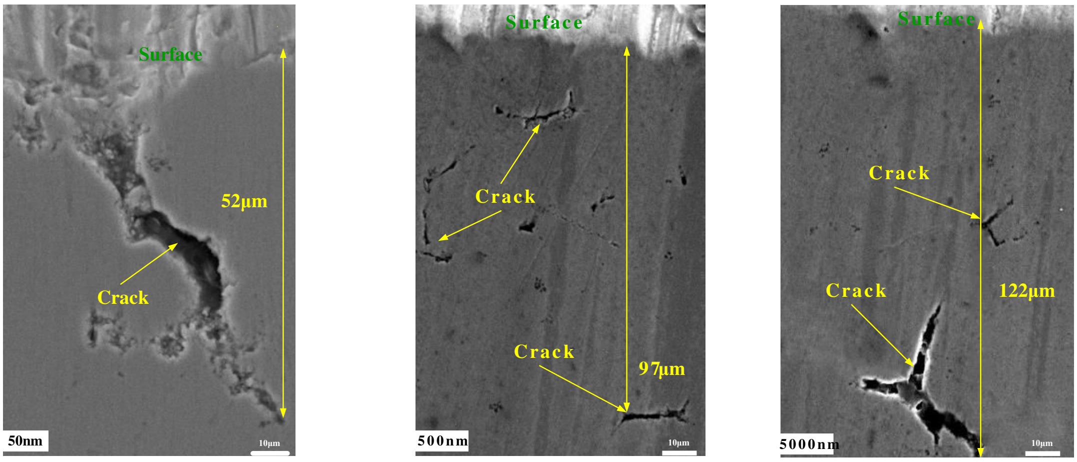
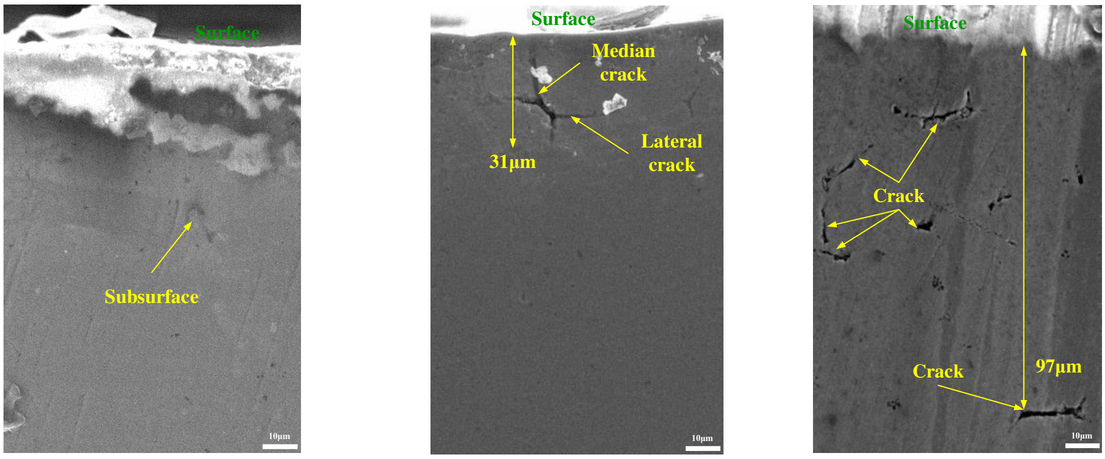


Fig. 7 Workpiece subsurface damage diagram under the 13th group (v_s =18.8m/s, v_w=20mm/s, a_p=15μm)



(v_s =9.4m/s, v_w=20mm/s, a_p=2μm) (a) the 1st group

(v_s =12.6m/s, v_w=20mm/s , a_p=5μm) (b) the 5th group

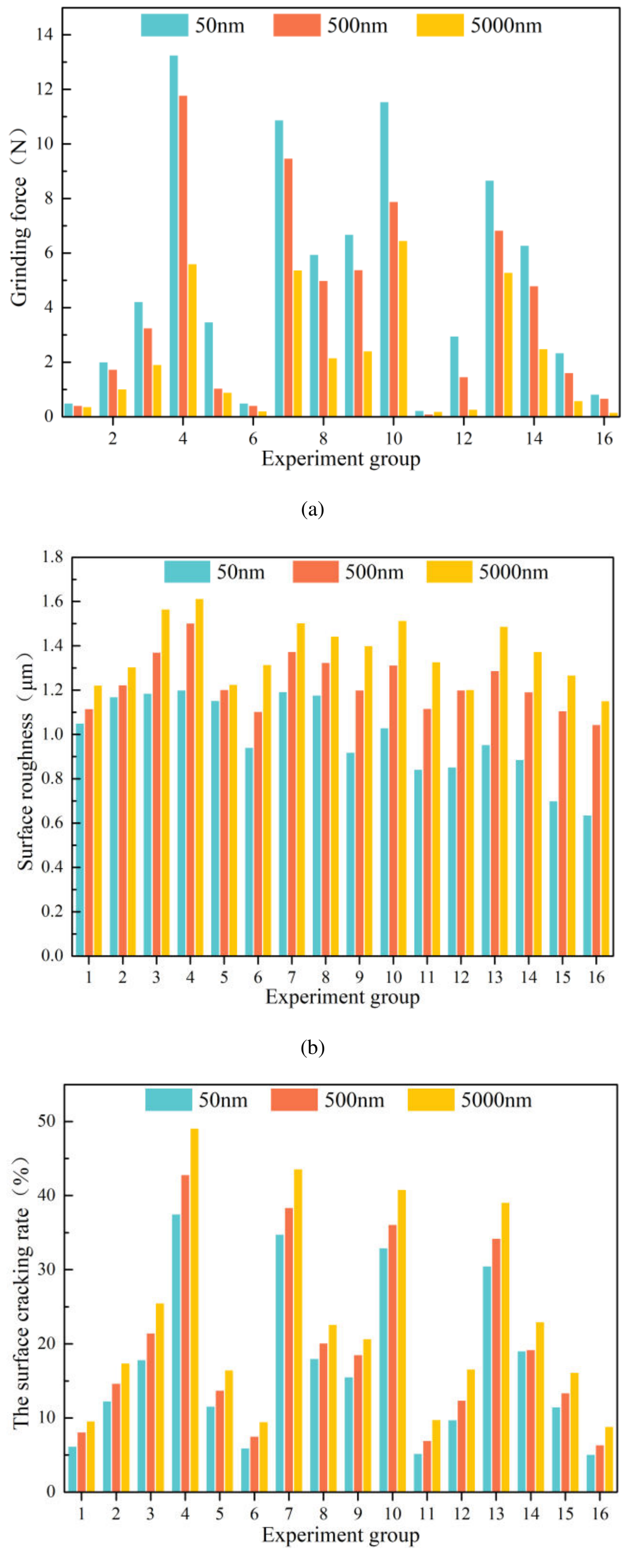
(v_s =18.8m/s, v_w=20mm/s, a_p=15μm) (c) the 13th group

Fig. 8 Subsurface damage diagram of 500nm ZrO_2 ceramic in grinding

3.4 Effect of grain size on grinding performance of ZrO_2 ceramic

From the above analysis, it is clear that the mechanical properties of ZrO2 ceramics are influenced by the grain size of the material, and the change in mechanical properties will inevitably affect the dynamic critical grinding force. Therefore, the surface quality of ZrO_2 ceramic with different grain sizes is not the same under the same process parameters. In order to analyze the influence of grain size on the grinding performance, grinding experiments of ZrO_2 ceramics were conducted in combination with Tables 1 and 2. The results are shown in Figure 9.

Fig. 9(a) illustrates how grain size increasing leads to a significant reduction in grinding force of ZrO_2 ceramic. The grinding force of ZrO_2 ceramics revealed a small variation in the range of 50nm to 500nm, but changed greatly from 500nm to 5000nm. When the grain size changes from 500 nm to 5000 nm, less force is required to remove the same volume of material with the same parameters. The reason for this change is that the larger the grain size, the easier it is for the grain surface to produce microcracks due to residual stress, making the grain more susceptible to deformation. At the same time, larger grain size contributes to crack extension by increasing the porosity inside the material and decreasing the grain boundary energy per unit area of the cracked surface. Therefore, as the grain size increases, the less energy required for material removal during grinding of ZrO2 ceramics, the lower the grinding force.



(a)

(b)

(c)

Fig.9 Comparison of grinding performance among three grain sizes(a)Effect of grain sizes on grinding force (b)Effect of grain size on surface roughness(c) Effect of grain sizes on the surface cracking rate

Fig. 9(b) shows the surface roughness of ZrO_2 ceramics with three grain sizes after grinding experiment. The increase of grain size leads to much less of grain boundaries and larger internal voids, the rougher the surface. At the same time, according to equation (8), it can be analyzed that the degree of influence of the change in dynamic fracture toughness on the critical grinding force is greater than the degree of influence of the change in hardness on the critical grinding force of ZrO_2 ceramics. Therefore, as the dynamic fracture toughness and critical grinding force increase due to the reduction of ZrO2 grain size, the percentage of ductile removal of ZrO_2 ceramics increases, hence the grinding surface quality is improved.

Fig.9(c) illustrates that the surface cracking rate of ZrO_2 ceramic gradually increases with the increment of grain size. Residual stress in the material is the main reason for the appearance and extend of the microcracks, which in turn leads to the fragmentation of the material; therefore, the surface cracking rate of ZrO_2 ceramic increases with the increment of grain size.

3.5 Effect of grain size on subsurface damage of ZrO_2 ceramic

The subsurface damage of three grain sizes under the 5^{th} group of grinding process parameters is shown in Fig. 10. Combined with Fig. 7 and Fig. 10, it is can be seen that the material removal of ZrO_2 ceramic with three grain sizes was ductile removal with no cracks on the workpiece surface and subsurface under the 1^{th} group, which is consistent with the results shown in Fig. 9(c).

In the 5^{th} group of grinding process parameters, the subsurface damage depth of ZrO_2 ceramics increased from 27μm to 31μm and 40μm in turn with the increase of grain size. When the grinding process was carried out under the 13th group of grinding process parameters, it was concluded from the above analysis that the material removal was brittle removal and cracks were produced in three different grain sizes of ZrO_2 ceramics, and the subsurface damage depth of ZrO_2 ceramics increased from 52μm, to 97μm, 122μm in order with the increase of grain size. According to Equation (9), there are many factors affecting the subsurface damage depth of ZrO_2 ceramic grinding, and the main factors affecting the subsurface damage depth of ZrO_2 ceramic grinding are the change of dynamic fracture toughness and the change of hardness, without considering the change of grinding process parameters, and the dynamic fracture toughness affects the subsurface damage depth more than the change of hardness. The dynamic fracture toughness has a greater influence on the depth of subsurface damage than the hardness, and the increase in grain size causes the dynamic fracture toughness to decrease, resulting in an increase in the depth of subsurface damage. Therefore, the subsurface damage depth of ZrO_2 ceramics with a grain size of 50 nm is much smaller than the other two under the same grinding process parameters. Finally, the subsurface damage depth of ZrO_2 ceramics is influenced not only by the process parameters, but also by the change in the mechanical properties of the material itself due to the change in grain size.

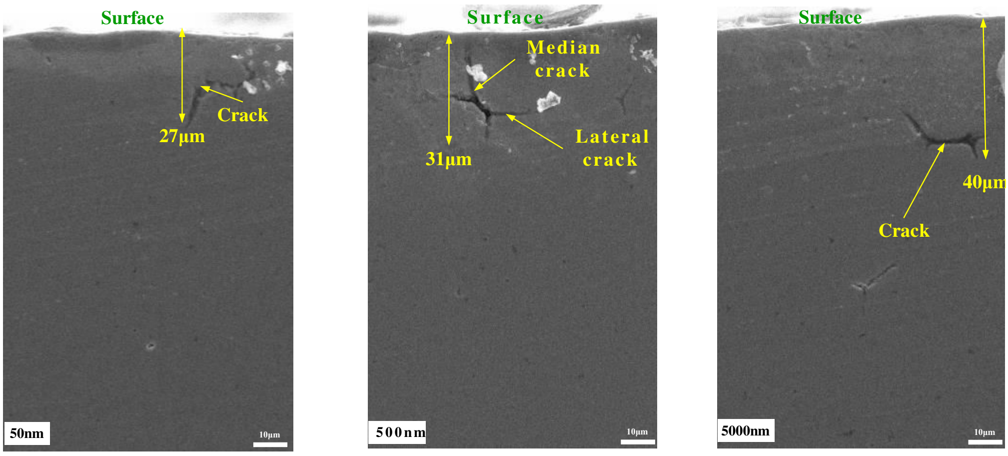


Fig. 10 Grinding subsurface damage of ZrO_2 ceramic with three grain sizes under the 5th group(v_s =12.6m/s, v_w=20mm/s, a_p=5μm)

4. Conclusion

In this paper, the dynamic critical grinding force and dynamic critical subsurface damage depth model for generating grinding cracks (transverse cracks and intermediate cracks) were established on the basis of considering the effect of dynamic fracture toughness, and the model was verified by experiments. Then, the effects of grinding process factors on the critical grinding forces and subsurface damage depths at different grain sizes were further analyzed. In addition, the effects of grain size on the grinding force, surface roughness, surface cracking rate and subsurface damage of ZrO_2 ceramics were also analyzed. The following detailed conclusions can be obtained.

1. It is concluded that the dynamic fracture toughness of ZrO_2 ceramics decreases nonlinearly with the increase of equivalent grinding thickness. On the basis of considering dynamic fracture toughness, a dynamic critical grinding force model for generating grinding cracks (lateral and median cracks) was developed, and the relevant factors affecting the grinding performance of ZrO_2 ceramic were analyzed. The dynamic critical grinding force model for brittle-ductile transition of ZrO_2 ceramics and its related parameters were determined. The accuracy of the model was verified by grinding experiments， and dynamic fracture toughness was introduced in the grinding process to expand the ductile removal range of ZrO_2 ceramics.
2. A dynamic maximum subsurface damage depth model for ZrO_2 ceramics was developed based on the dynamic fracture toughness. Static, dynamic and actual value of the maximum subsurface damage depth were compared. The results show that the dynamic maximum subsurface damage depth is closer to the actual maximum subsurface damage depth, while the static maximum subsurface damage depth has a large different from the actual value. The dynamic maximum subsurface damage depth model of ZrO_2 ceramics was experimentally validated to facilitate the prediction of critical grinding forces and maximum subsurface damage depths.
3. The effects on grinding performance (grinding force, surface roughness, surface crushing rate and subsurface damage) of ZrO_2 ceramics with three grain sizes were analyzed. With the reduction of grain size, the mechanical properties and the grinding performance is excellent which indicates that the surface quality of the workpiece can be effectively improved.

Declarations

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Conflicts of Competing Interest

We confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Availability of data and material

We confirm that data is open and transparent.

Code availability

Not applicable.

Authors' contributions

Can Yan: Conceptualization Investigation, Writing-original draft, Writing-review & editing.

Zhaohui Deng: Writing-review & editing, Funding acquisition.

Tao Xia: Data Curation, Formal analysis, Writing-review & editing.

Wei Liu: Writing-review & editing.

Hua Zhang: Writing-review & editing.

References

[1] V.T. Shmuradko, F.I. Panteleenko, O.P. Reut, Engineering Ceramics: Materials and Objects, Principles of Composition, Structure, and Property Formation, Refractories and Industrial Ceramics 60(2019) 204-208.

[2] B. Zhang, X. Zheng, H. Tokura, M. Yoshikawa, Grinding induced damage in ceramics, Journal of materials processing technology 132 (2003) 353-364.

[3] H. Tang, Z. Deng, Y. Guo, J. Qian, D. Reynaerts, Depth-of-cut errors in ELID surface grinding of zirconia-based ceramics, International Journal of Machine Tools and Manufacture 88 (2015) 34-41.

[4] L. Wan, L. Li, Z. Deng, Z. Deng, W. Liu, Thermal-mechanical coupling simulation and experimental research on the grinding of zirconia ceramics, Journal of Manufacturing Processes 47(2019) 41–51.

[5] X. Yang, Z. Qiu, X. Li, Investigation of scratching sequence influence on material removal mechanism of glass-ceramics by the multiple scratch tests, Ceramics International 45(2019) 861-873.

[6] J. Wang, X. Zhang, F. Fang, R.T. Chen, A numerical study on the material removal and phase transformation in the nanometric cutting of silicon, Applied Surface Science 455(2018) 608-615.

[7] C. Li, F. Zhang, B. Meng, L. Liu, X. Rao, Material removal mechanism and grinding force modelling of ultrasonic vibration assisted grinding for SiC ceramics, Ceramics International 43(2017) 2981-2993.

[8] X. Li, Study of the material removal mechanism of glass-ceramics based on consecutive incremental loading in ductile-regime grinding, Nanotechnology and Precision Engineering 3(2020) 88-95.

[9] P. Li, T. Jin, H. Xiao, Z. Chen, M. Qu, H. Dai, S. Chen, Effects of wheel speed on surface/subsurface damage characteristics in grinding of glass-ceramics, Ceramics International 46(2020)17717-17728.

[10] Y. Yan, C. Li, B. Zhao, H. Ma, Research on grinding force characteristics of nano-ZrO_2 ceramic by two-dimensional ultrasonic grinding, China Mechanical Engineering (2008)1270-1274

[11] L. Tian, Y. Fu, J. Xu, H. Li, W. Ding, The influence of speed on material removal mechanism in high -speed grinding with single grit, International Journal of Machine Tools and Manufacture 89(2015)192-201.

[12] J. Dai, H. Su, T. Yu, H. Hu, W. Zhou, W. Ding, Experimental investigation on materials removal mechanism during grinding silicon carbide ceramics with single diamond grain, Precision Engineering 51(2018) 271-279.

[13] M. Yang, C. Li, Y. Zhang, D. Jia, X. Zhang, Y. Hou, J. Wang, Maximum undeformed equivalent chip thickness for ductile-brittle transition of zirconia ceramics under different lubrication conditions, International Journal of Machine Tools and Manufacture 122(2017) 55-65.

[14] X. Yang, B. Zhang, Material embrittlement in high strain-rate loading, International Journal of Extreme Manufacturing 12 (2019) 003-022.

[15] S. Gao, X. Zhu, R. Kang, D. Guo, Z. Wang, B. Zhang, Study on Surface/Subsurface Damage and Material Removal Mechanism in Ultra-precision Grinding of Glasses, Journal of Mechanical Engineering 53(2017) 180-188.

[16] C. Li, F. Zhang, X. Zhang, X. Rao, Research progress of ductile removal mechanism for hard-brittle single crystal materials, Journal of Mechanical Engineering 55(2019) 181-190.

[17] X. Yang, Z. Qiu, C Lu, X. Li, J. Tang, Modelling the strain rate sensitivity on the subsurface damages of scratched glass ceramics, Ceramics International 43(2017) 12930-12938.

[18] C. Wang, Q. Fang, J. Chen, Subsurface damage in high-speed grinding of brittle materials considering kinematic characteristics of the grinding process, The International Journal of Advanced Manufacturing Technology 83 (2016) 937-948.

[19] B. Meng, D. Yuan, S. Xu, Coupling effect on the

removal mechanism and surface/subsurface characteristics of SiC during grinding process at the nanoscale, Ceramics International 45(2019) 2483-2491.

[20] R.J.Clifton, Analysis of Failure Waves in Glasses, Applied Mechanics Reviews 46(1993).

[21] J.J.M. Machadoa, A. Hayashib, Y. Sekigushib, R.D.S.G. Campilhoc, E.A.S. Marquesa, C. Satob, L.F.M.da Silvad, Dynamic behaviour in mode I fracture toughness of CFRP as a function of temperature, Theoretical and Applied Fracture Mechanics 103(2019) 102-257.

[22] J.J.M. Machadoa, E.A.S. Marquesa, R.D.S.G. Campilhoc, D. Silva, F.M. Lucas, Mode II fracture toughness of CFRP as a function of temperature and strain rate, Journal of Composite Materials 114 (2017)311-318.

[23] R.J. Anton, G. Subhash, Dynamic Vickers indentation of brittle materials, Wear239(2000) 27-35.

[24] S. Suresh, T. Nakamura, Y. Yeshurun, K. H. Yang, J. Duffy, Tensile fracture toughness of ceramic materials: effects of dynamic loading and elevated temperatures, Journal of the American Ceramic Society 73(1990) 2457-2466.

[25] G. Xie, Z. Shang, X. Sheng, Y. Wu, J. Yu. Grinding force modeling for high-speed deep grinding ofengineering ceramics, Journal of Mechanical Engineering 47(2011) 169-176.

[26] J.F. Kalthoff, S. Winkler, W. Bohme, A novel procedure for measuring the impact fracture toughness K_{Id} with precracked Charpy specimens, Le Journal de Physique Colloques 46 (1985) 179-186.

[27] M. Yang, C. Li, Y. Zhang, D. Jia, R. Li, Y. Hou, H. Cao, Effect of friction coefficient on chip thickness models in ductile-regime grinding of ZrO_2 ceramic, The International Journal of Advanced Manufacturing Technology 102(2019) 2617-2632.

[28] M. Yang, C. Li, Y. Zhang, D. Jia, X. Zhang, Y. Hou, R. Li, J. Wang, Maximum undeformed equivalent chip thickness for ductile-brittle transition of zirconia ceramics under different lubrication conditions, International Journal of Machine Tools and Manufacture 122(2017) 55-65.

[29] Y. Liu, B. Li, C. Wu, L. Kong, Y. Zheng, Smoothed particle hydrodynamics simulation and experimental analysis of SiC ceramic grinding mechanism, Ceramics International 44(2018) 12194-12203.

[30] C. Wu, B. Li, Y. Steven, A critical energy model for brittle–ductile transition in grinding considering wheel speed and chip thickness effects, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 230 (2016) 1372-1380.

[31] C. Wu, J. Ni, J. Yang, Y. Steven, High-speed grinding of HIP-SiC ceramics on transformation of microscopic features, The International Journal of Advanced Manufacturing Technology 102 (2019) 1913-1921.

[32] B. Li. J. Ni, J. Yang, Y. Steven, Study on high-speed grinding mechanisms for quality and process efficiency, The International Journal of Advanced Manufacturing Technology 70 (2014) 813-819.

[33] X. Yang, B. Zhang, Q. Bai, M. Zheng, J. Tang, Grain size influence on chip formation in high-speed machining of pure iron, The International Journal of Advanced Manufacturing Technology 108(2020) 1357-1366.

[34] H. Demir, A. Gullu, I. Ciftci, U. Seker, An investigation into the influences of grain size and grinding parameters on surface roughness and grinding forces when grinding. Journal of mechanical engineering 56(2010) 447-54.

[35] S. Kannappan, S. Malkin, Effects of grain size and operating parameters on the mechanics of grinding, Journal of Engineering for Industry 94(1972) 833-842.

[36] Z. Deng, Q. Jin, B. Zhang, Critical grinding condition model for predicting grinding induced lateral cracks in nanostructured ceramic coatings, Key Engineering Materials 259(2004) 273-277.

[37] Z. Yang, L. Zhu, L. B, G. Zhang, B. Chen, T. Sui, The grinding force modeling and experimental study of ZrO2 ceramic materials in ultrasonic vibration assisted grinding, Ceramics International 45 (2019) 8873- 8889.

[38] Z. Deng, B. Zhang, Z. Sun, Research progress of material removal mechanism in ceramic grinding, China Mechanical Engineering 13(2002) 1608-1611.

[39] F. Yang, B. Zhang, J. Wang. The effect of grinding machine stiffness on surface integrity of silicon nitride, Journal of Manufacturing Science and Engineering 123(2001) 591-600.

[40] T.G. Bifano, T.A. Dow, R.O. Scattergood, Ductile-regime grinding: a new technology for machining brittle materials, Journal of Manufacturing Science and Engineering 113(1991)184-189.