# RESEARCH ON GAS PRESSURE SINTERING ZIRCONIA SURFACE QUALITY BASED ON INTERNAL GRINDING

**He Wang[1,2,], Yuhou Wu[1,2], Peng Zhou[2], Ke Zhang[2]**

**ABSTRACT**: The application of zirconia parts are limited by structure and machined surface quality. Precision grinding is one of the most efficient ways to improve surface quality. The MK2710 grinder and resin bond diamond wheel were used in zirconia grinding. The specimen grinding surface morphology were obtained by SEM. The paper focused on wheel speed, grain size and the affect of grinding depth on surface roughness and the removal mechanism, and determined the roughness change ruler. The research results indicate that decreasing the grain size and grinding depth, and increasing wheel speed could decrease specimen surface roughness and increase grinding surface quality. The results can improve ceramic parts surface quality and promote application.

**KEY WORDS**: zirconia, grinding, ceramic, diamond wheel.

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## 1 INTRODUCTION

Zirconia ceramic which developed from 1970's has excellent mechanical properties. It is widely used in metallurgy, mechanics, aerospace and chemical fields, but the machining transformation is the key problem in application [1,2]. Zirconia transformation among cubic, tetragonal and monoclinic phase because the temperature change in sintering; the t→m transformation due to stress in machining. Because of the material characteristics, it produces cracks and fractures easily, the application is limited. Zirconia preparation and machining technology are key problems affecting characteristics.

S. Malkin analyzed the ceramic grinding mechanism based on the indentation fracture principles, analyzed the grinding energy and the removal relation by surface residual stress and $Si_3N_4$ debris examined [3]. K. Kitajima, G. Q. Cai researched the grinding force and SEM of SiC and $Si_3N_4$ compared to $Al_2O_3$, and the material grindability related to temperature [4]. G. Warnecke, U. Rosenberger, J. Miberg researched parameters selected and analyzed the creep feed, grinding depth and work piece speed affected on surface damage [5].

Bi Zhang researched the ceramic material grinding removal mechanism through $Si_3N_4$ and $Al_2O_3$ grinding, and the powder regime rather than ductile regime has been observed in single-point grinding of ceramics [6].

[1] National-Local Joint Engineering Laboratory of High-Grade Stone Numerical Control Machining Equipments and Technology, Shenyang 110168, China

[2] School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang 110168, China

G. Warnecke analyzed the wheel dynamic characteristics when grinding hard and brittle materials by finite element, changed the wheel parameters to meet the surface roughness requirements [7]. E. Uhlmann analyzed the creep feed ultrasonic grinding ceramic surface forming mechanism, and found the ultrasonic assisted grinding can improve removal efficiency by SEM tested, residual stress and bend test, but sub-surface had no damage [8]. Bi Zhang researched machine system stiffness influence on ceramic grinding, and found that the residual workpiece strength is mainly affected by the dynamic component, rather than the static component, of the normal grinding force [9]. T. Matsuo, M. Touge ground the ceramic with the superfine grain diamond cup wheel, and found the grain and grind depth affect on removal model [10]. A. B. Yu researched on $Al_2O_3$ honing removal mechanism and found that increasing honing pressure can improve the material removal rate [11]. J. Y. Shen researched ceramic constant pressure grinding and found the relation between the grinding pressure and machine cracks [12]. H. Huang ground three ceramic materials, the results indicated that the material removal mechanism was relative to high speed deep grinding, and was effected by morphology and material characteristics [13]. Chien-Cheng Liu researched $Si_3N_4$ grinding depth and the worktable speed effect on surface reliability [14]. K. Katahira researched AlN ceramic ELID grinding characteristics and surface forming, the roughness reached 0.008μm [15]. Ling Yin used the 160μm grain resin bonded grinding wheel to grind ceramic, and found the $ZrO_2$ removed in plastic model and the surface quality didn't improve [16]. E. Brinksmeier summarized the super fine grinding technology, and explored how to reduce cracks on surface [17]. Jianyi Chen used brazed diamond wheels to grind ceramic at high speed, the results indicated the different ceramic removal mechanism at high speed weren't the same, and analyzed the grinding energy consumption [18]. Sanjay Agarwal built a new undeformed chip thickness prediction model based on grain high random distribution and the sectional of groove supposed arc [19]. G. F. Gao researched nano-zirconia ceramics supersonic grinding and found the wheel speed and grinding depth had a large influence on surface roughness [20]. Sanjay Agarwal grinded silicon carbide and revealed the material mechanical properties effect on surface integrity at a high removal rate [21]. Han Huang ground $Si_3N_4$ ceramic by resin bond diamond wheel, and focused on the speed effect on the removal mechanism and the surface quality [22]. Jie Feng analyzed the ceramic grinding surface forming mathematical model by track and finite element coupling [23]. J. Feng researched tool wear monitoring in ceramic grinding, and analyzed tool wear and stiffness effect on grinding force, grinding system vibration and spindle load signal [24]. Mohammad Rabiey used metal-vitrified bond diamond wheel grind zirconia, the results indicated the wheel had advantages compared to traditional wheel and had good dressability [25].

$ZrO_2$ ceramic microstructure and machined surface have large effects on performance. There are many $ZrO_2$ machining ways, but grinding is the most widely used. The research on zirconia grinding mainly focuses on plane grinding, the internal grinding mechanism and technology needs improving and perfection. The paper analyzed grinding parameters affect on surface roughness and removal model in zirconia internal grinding, analyzed and found appropriate parameters to improve surface grinding quality.

## 2 SPECIMENS AND EXPERIMENTAL EQUIPMENTS

### 2.1 Zirconia specimens

$ZrO_2$ ceramic specimens are obtained after cooling from a high temperature sintering of $ZrO_2$ ceramic powders (Fig. 1). The pure $ZrO_2$ is difficult to sinter densely mainly due to the temperature being reduced after high temperature sintering, and t→m phase change is caused, thus resulting in the cracks and reduction of material strength. Currently, $ZrO_2$ ceramics are processed through toughening with the main methods of transformation toughening, microcracks toughening and surface toughening etc. In the experiment, yttria (2.5%) - aluminum (0.25%) are used as the catalyst, after a gas pressure sintering at 1450 ℃ for 4h, SEM observation is conducted for the sintered surface after its cooled down.

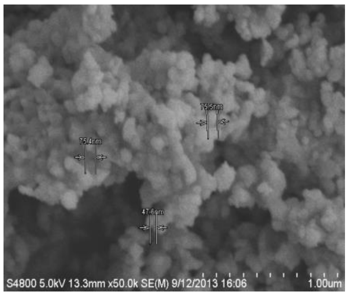
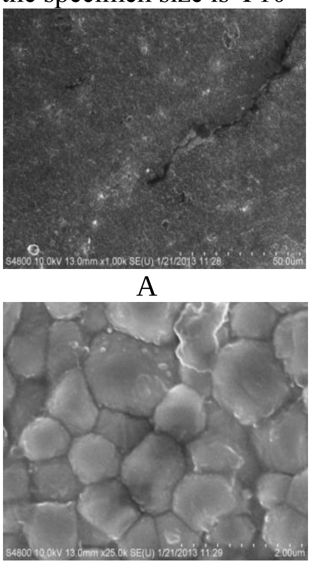



**Fig. 1 Powders SEM**.

(Fig. 2) shows the surface appearance of the ceramic material after sintering. As it can be seen from (A), the surface of the sintered ceramic material is uneven with cracks. The formation of the cracks are related to the powder grinding, isostatic molding and sintering process. (B) shows the enlarged surface condition, from which $ZrO_2$ ceramic grain boundaries after sintered can be clearly seen. The microstructure of the ceramic surface of the prepared zirconia is all t-$ZrO_2$ grains. Through the phase transformation toughening, phase t is transformed to phase m in crack stress. The purpose of improving the fracture toughness is achieved by the volume expansion bridging cracks of phase transition. The surface after sintered is the zirconia particle with the size of about 860nm. The performance index of zirconium oxide is as shown in (Table 1), and the $ZrO_2$ ceramic specimen finally formed as shown (Fig. 3), and the specimen size is Φ10 × 7-Φ7 × 8.



A

B

**Fig. 2 Surface after Sintering**.

**Table 1. $ZrO_2$ Performance Parameters.**

| Parameters | Value |
|---|---|
| Density g/cm | 6.0 |
| bending strength MPa | 950 |
| fracture toughness Mpa.m$^{1/2}$ | 9.0 |
| thermal expansion coefficient $10^{-6}$/°C | 10.5 |
| Hardness HV kg/mm$^2$ | 1100 |
| elastic modulus GPa | 210 |

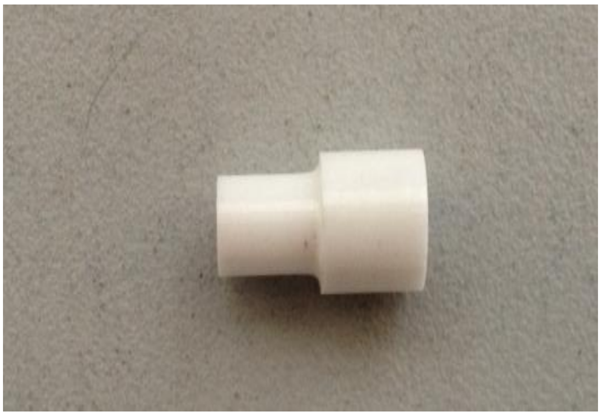


**Fig. 3 $ZrO_2$ ceramic specimens.**

## 2.2 Experiment equipments

In the experiments, MK2710 CNC internal and cylindrical composite grinding machine as shown in (Fig. 4) is used to conduct the internal grinding for the ceramic specimens. The maximum spindle speed is 36000r/min, feed resolution is 1μm, workpiece revolving speed is 14.73m/min, and it shall be cooled down by using the water-based coolant prepared with the emulsion and water at 1:20. The wheel parameters for experiments are shown in (Table 2).

**Table 2. Wheel Parameters.**

| Bond | Grain size | Concentration | Wheel diameter | Wheel thickness |
|---|---|---|---|---|
| resin | 60#、120#、240#、W20 | 100% | 55mm | 5mm |

After grinding the specimen, the Taylor Hobson roughness tester was used to measure the Ra value of finished surface roughness.

The surface morphology is measured by the S-4800 field emission scanning electron microscope, and the device can be used to magnify the image up to 0.8 million times

**Fig. 4 MK2710 Grinder.**

The experiment researched the impact of parameters such as grinding wheel grain, wheel speed and grinding depth on the grinding removal mechanism and surface quality. The grinding parameters used in the experiments are shown in (Table 3).

**Table 3. Grinding Parameters.**

| Grinding speed | Grinding depth | Grinding width | Shaking speed | Grinding model |
|---|---|---|---|---|
| 23～75m/s | 2～20μm | 4mm | 40mm/min | Upgrinding |

## 2.3 Grinding mechanism

The maximum undeformed chip thickness provides the basis for predictions of roughness. The $h_{max}$ can be calculated as[18]:

$$h_{max} = \left[\frac{3}{C \cdot \tan\theta}\frac{v_w}{v_s}\sqrt{\frac{a_p}{d_s}}\right]^{1/2} \quad (1)$$

where $C$ is the active grit density, $\theta$ the semi-included angle of the active grit point and $\theta$=60° is often used, $d_s$ the wheel diameter. The $\theta$, $v_w$, $v_s$, $a_p$ and $d_s$ affect the surface roughness.

The maximum undeformed chip thickness and critical depth of penetration related to zirconia grinding mechanism. The ductile mode material removal could be achieved when the specific material removal volume is sufficiently small. The critical depth of cut can be written as[22]:

$$h_c = \beta\left(\frac{E}{H}\right)\left(\frac{K_{IC}}{H}\right)^2 \quad (2)$$

where $\beta$ is a constant related to the wheel topography, $E$ the elastic modulus, $H$ the hardness and $K_{IC}$ the fracture toughness. The above parameters are material characteristics, have little relation to grinding. So the $h_c$ is constant.

In order to reveal the grinding surface roughness and removal mechanism. The paper focuses on these parameters affect on roughness.

## 3 EXPERIMENT RESULTS AND ANALYSIS

### 3.1 Grain size affect on surface quality

Grain size is the most important factor affecting the surface quality and removal mechanism in grinding. In the paper, the different grain sizes wheels are used to grind the zirconia ceramic with the grinding depth of 8μm. The grinding wheel velocity among 23～75m/s, and the grinding surface roughness change curve is shown in (Fig. 5).

As can be seen from (Fig. 5), under the condition that the other conditional parameters remain the same, with the decreasing of abrasive grain size, it is more significant for the roughness decreasing, which shows that grain size has the larger impact on the grinding surface roughness. The reason is that for the grinding wheel with the same concentration, when the grain size increases, the grain amount in the unit surface of the grinding wheel decreases, the spacing of the grain and height of the projecting grinding wheel surface is high, and the grain amount crossed in the specimen unit area is less with the deep scratches, thus resulting in the increase of specimen surface roughness.

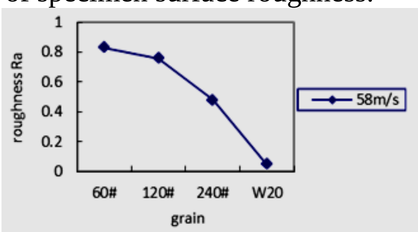
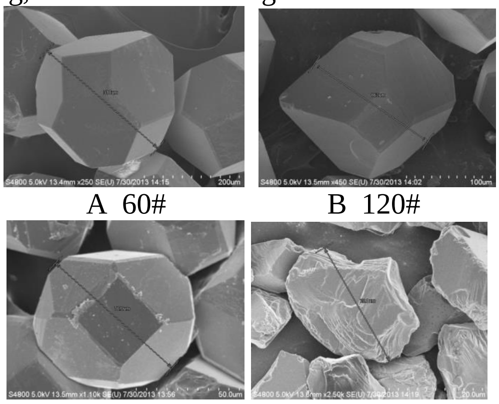



**Fig. 5 Grain size affect on roughness**.

To further explain the impact of grinding wheel grain size on the experiment surface roughness, the micro powders used to manufacture four grinding wheels had the Scanning Electron Microscope (SEM) respectively, and the results are as shown in (Fig. 6). The figure shows that grains of 60#, 120# and 240# form the polyhedral shapes, which are mostly dodecahedrons; the grains of W20 are mostly irregular polyhedrons. The grinding wheel grains size of 60#, 120#, 240# and W20 are 310μm, 163μm, 76μm and 28.1μm respectively. Generally, the amount of grains distributed on the grinding wheel surface is related to the dimensions. The larger the abrasive particle size, the less amount they distributed on the surface. Furthermore, it can be seen from the figure that the shapes of the first three grains are regular, which are mainly in obtuse angle; while the abrasive particles of W20 are irregular, which formed much vertex angles can be used for cutting. They have small area of contact with the workpiece and it is easy to cut into. It can be removed from the ceramic surface by micro-cutting, and the surface roughness value is lower.



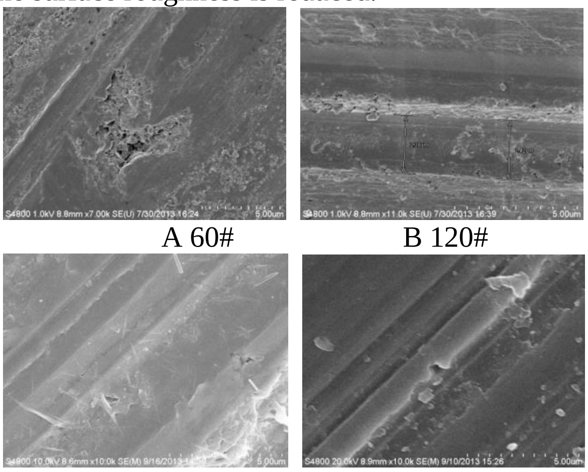
A 60# B 120#

C 240# D W20

**Fig. 6 Diamond grains morphology**.

The dimensional changes of the grains will cause the changes of protruding height of wheel surface and the spacing between the grains, and the groove depth and spacing change in grinding surface. The $ZrO_2$ ceramic specimen surface SEM image shows (Fig. 7), which grinded by 60#, 120#, 240# and W20 wheels.

The (Fig. 7) shows that the surface grinded by 60# wheel is mostly fragmentation, and there are obvious cracks with the wide surface grooves; the surface grinded by 120# wheel the crushing proportion is still large, but width of trace scratched by grain became narrow, which shows part of the plastic deformation and uplift; the surface generated by #240 wheel differs from the previous; there are obviously scratched groove and plastic uplift, as well as the plastic deformation. In addition, the scratched grooves width are relatively uniform and the groove spacing decreased; the groove width of the surface scratched by W20 wheel grinded is narrow and dense, which shows the greater difference with the surface formed by the previous three grain wheels: the groove is shallow and relatively dense, the surface is relatively smooth, and the removal is mainly plastic, without obvious cracks. It can be known from the definition of Roughness Ra: with the grains size increasing, the grains spacing increasing, and the depth of grinding will increase, with the surface contour offset distance value increasing in the length of the sampling, the value of roughness Ra also increases. For the grain with larger size, as it’s distance protruding from wheel surface is larger, the protruding height of the grains is uneven, the cutting depth vary widely while cutting, and the surface is formed by a variety of removal models; for the smaller grains, the height protruding from the surface of the wheel is uniform and the spacing is small, the cutting depth is also uniform and the removal model is relatively simple, the formed surface groove depth and spacing are uniform, and the surface roughness is reduced.



A 60#  B 120#

C 240#  D W20

**Fig. 7 Grinding surface morphology by different grains wheel**.

From the definition of Roughness $R_a$

$$R_a = \frac{1}{l}\int_0^l |y(x)|\,dx \tag{3}$$

where *y*-- contour offset distance (distance between each point on the contour to the reference line);*l*-- sampling length.

With the grains size increasing, the grains spacing increases, and the depth of grinding increases, hence the value of the sampling length y increases, from the formula (3), it is known that the value of $R_a$ also increases. The size of grains poses a greater impact on the roughness of the grinding surface.

The impact of grains size on the grinding surface is mainly through the different grains protruding height and different spacing, the cutting depth and spacing are changed in surface grinding. For the grains with larger size, due to the protruding wheel surface is larger, and the height of the grains is uneven and the cutting depths vary widely in grinding. The machined formed surface combined by a variety of removal models; for the smaller grains, the height protruding from the surface of wheel is uniform and the spacing is small, the cutting depth is also uniform and the removal models are relatively simple, the groove depth and spacing are uniform on the surface, and the surface roughness is reduced.

## 3.2 Wheel velocity impact on surface quality

(Fig. 8) shows the impact of the grinding wheel speed on the grinding surface quality at grinding depth of 8μm. The figure shows that with the increasing of the wheel speed, $ZrO_2$ ceramic specimen surface roughness was reduced, and the the machined surface quality was improved. This is because: under certain conditions of the feed and cutting depth, the lower wheel speed caused the lower relative speed between the grains and the workpiece, and reduced the number of grains passed per unit of time, thus resulting cutting depth of the single grain depth increased, and the roughness increased; meanwhile, the force between each grain and the workpiece surface is increased; the larger force will cause the fracture of surface and form the material brittleness removal and increase the roughness; while the increase of wheel speed can reduce the cutting action of a single grain passing the workpiece surface for the single time, and mitigate the fractures occurred due to the squeeze of the grains on the workpiece; meanwhile, the grinding speed increases, and the times of a single grain passing the workpiece surface in the unit time is increased while the single grain single grinding depth is reduced, thus it is beneficial to the materials ductile grinding and reduction of the surface roughness.

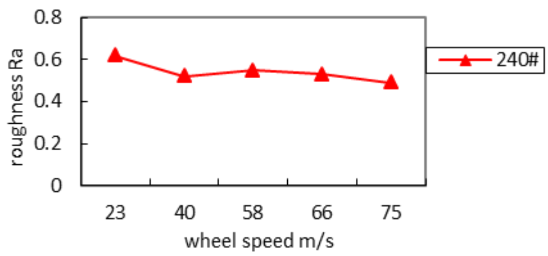



**Fig. 8 Surface roughness changing curve at different grinding wheel speed**.

(Fig. 9) shows the micro-morphology of $ZrO_2$ ceramic specimen grinded surface by 240# wheel at different speeds. The figure shows that there are scratches, brittle fractures and the ductile deformation on the surface at 23m/s. With the wheel linear speed increasing, the grooves formed by the grains scratch on the processed surface of the ceramic material gradually become uniform, and the spacing is decreased; a greater proportion of ductile deformation on the surface at 75m/s, and the spacing of grooves formed by scratching of grains decreases due to plastic deformation, the material ductile removed obviously. Based on grinding mechanism, increasing wheel speed the number of grains contact with the workpiece per unit time will increase, and the grinding amount of the single particle will decrease and the grinding depth is reduced, thus increased the material ductile removal

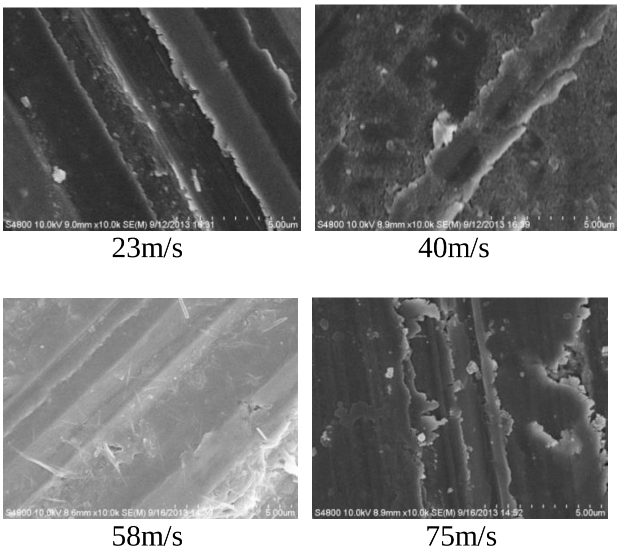



**Fig. 9 grinding surface by 240# wheel at different speeds.**

### 3.3 Impact of grinding depth on roughness and removal mechanism

(Fig. 10) shows the impact of the grinding depth of the W20 wheel on the $ZrO_2$ ceramic specimens' surface roughness. The figure shows that with the increasing of grinding depth, the surface roughness increases, and the surface quality is decreased. This is because the grinding depth increased the force of a single grain on the workpiece surface increases; the ductile removal rate decreased, and the brittle crack removal rate increases, resulting in increased surface roughness. The figure also shows the grinding wheel speed among 58～66m/s, the surface roughness of the workpiece is small, and the surface quality is high, which indicates W20 wheel grinding the $ZrO_2$ ceramic specimens at 58～66m/s speed can obtain higher surface quality. The possible reason is that when W20 wheel speed is higher than 66m/s, the tool system vibration may cause the increase of surface roughness.

The some surface micro-morphology SEM results of above three different grinding depths at different grinding speed is shown in (Fig. 11).

As can be seen from figure that the removing model is mainly ductile removal used W20 wheel grinding, but as can still be seen in the figure there is the part of brittle fracture. When the wheel speed at 23m/s, the distance between each of the surface grinding grooves is larger, the distance is about 2μm.

When at 40 m/s, the surface traces spacing grinded by grains is reduced significantly, which is

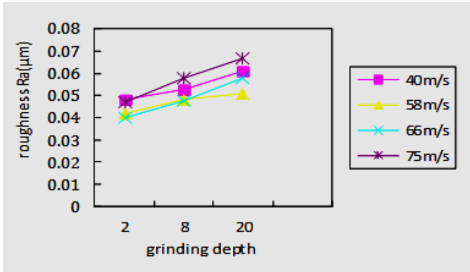



**Fig. 10 roughness curve of different grinding depth.**

of about 0.7～1.5μm, and the proportion of material ductile removal increases, and the surface quality is improved greatly compared with before. When the wheel speed is of 58 m/s, the surface micro-morphology in the three grinding depth conditions is basically the same, which is mainly plastic deformation removal. The traces of brittle fracture on the surface are less, and the spacing between the grinding grooves is uniform and small, the roughness is reduced; but the microscopic surface brittle fractures are increased compared with the previous conditions when the speed was increased to 75m/s, and the surface present the uneven machined stripe width, and the surface roughness increases.

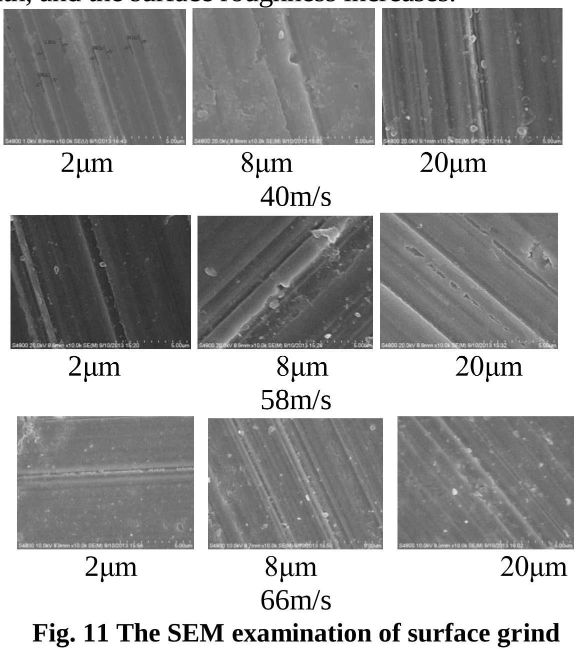



**Fig. 11 The SEM examination of surface grind by W20 in different grinding depths.**

## 4 CONCLUSION

Through the experiments research and analysis, the following conclusions are reached:

1) With the increasing of wheel grains size, the number of diamond grains on the wheel surface unit area is less, and the wheel surface single grain increases cutting depth and the force on $ZrO_2$ ceramic surface; the $ZrO_2$ ceramic material brittle crack removal increases in grinding, resulting in the

increase of workpiece surface roughness and the degradation of the surface quality;

2) When the wheel speed increases, the scratching times of single abrasive of the grinding wheel in unit time on $ZrO_2$ ceramic surface increases, and the single abrasive grinding depth in single time decreases, $ZrO_2$ ceramics material ductile removal rate increases, the workpiece surface roughness is reduced and the surface quality is improved; the brittle and ductile removal composed the surface, and difficult to found the complete ductile removal.

3) The grinding depth increases, the grinding depth of the single abrasive on $ZrO_2$ ceramics will also increase, the force increases, material brittle removal rate increases, and the surface quality will be reduced; for W20 grinding wheel, when the grinding wheel speed is at 58～66m/s, it is possible to obtain the high-quality ceramic $ZrO_2$ specimen surface.

## 5 ACKNOWLEDGEMENTS

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