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Effect of porosity on the grinding performance of vitrified bond diamond wheels for grinding PCD blades

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Abstract

In this paper, the preparation of nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond diamond tools with various porosities is reported. The effects of porosity on the impact strength and grinding properties of the wheels for grinding PCD blades are also discussed. The results show that the porosity not only affects the impact strength of the wheels but also the grinding properties, such as the grinding efficiency, the self-dressing, the service life and the surface roughness of the work pieces. The optimum porosity for nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond diamond wheels for grinding PCD tools is approximately 40.5 vol%.

Keywords: B. Porosity; Vitrified bond diamond tools; Impact strength; Grinding

1. Introduction

Compared with conventional cemented carbide and high-speed steel, polycrystalline diamond (PCD) exhibits exceptional properties, such as higher hardness and wear resistance. PCD tools provide an ideal solution for many high speed machining applications for several materials, including aluminum alloy, magnesium alloy, titanium alloy, zirconium alloy, non-ferrous metal materials, cemented carbide, and ultra-hard materials. This leads to a consistent increase in demand for PCD tools [1–3]. However, due to the high hardness of PCD, it is challenging to find a grinding tool to machine the PCD tools themselves. Vitrified bond diamond wheels could provide a tool with a superior efficiency in grinding PCD tools [4–6]. The porosity and structure of the wheels can be controlled, allowing their strength to be more precisely adjusted and, at the same time, allowing the grinding products to be removed more easily [7]. The flexibility of the vitreous bond system makes it possible to condition the topography of this type of wheel to achieve a broad range of removal rates and surface finish characteristics [8]. The porosity is an important structural constituent in vitrified bond diamond wheels. For brittleness materials of vitrified bond diamond wheels, properly designed pores distributed between the bond bridges can restrain crack propagation and increase the impact strength of vitrified bond diamond wheels. However, the pores can also inflect the bond bridge. Such a structural possibly can reduce the frictional heat generated during grinding by reducing the contact area and by allowing the flow of cooling fluid in the pores. Therefore, the porosity of the vitrified bond diamond wheels has a significant effect not only on the performance and grinding efficiency but also on the surface quality of the work pieces [9–12]. Hence, to achieve the highest removal rates and surface finish characteristics, the porosity and size of pores for the vitrified bond diamond wheels must be accurately controlled.

In this work, nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond diamond wheels with varying porosities were prepared for grinding PCD tools by adding pore-forming agents, and the effects of porosity on the grinding efficiency, the service life, and the surface finish characteristics of the PCD tools were investigated. The results of

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this investigation will assist in developing a new high quality nano-AlN modified $Na_2O–B_2O_3–SiO_2$ vitrified bond diamond wheel with optimum porosity.

2. Experimental

In this work, the type straight cup wheel 6A2 with a size of $150 \times 40 \times 40 \times 15 \times 8$ mm (outer diameter × overall thickness × bore diameter × rim width × thickness of abrasive section) was prepared. The grain size of the diamond is 12–22 μm. The basic vitrified bond of $Na_2O–B_2O_3–SiO_2$ glass was fired to pre-fritted glass, which was subsequently crushed and seized to produce a fine, powdered glass. A part of the basic vitrified bond was then mixed with 6 wt% nano-AlN powder of the size 40 nm and the purity 99%, as well as 20 vol% diamond and 3–10 vol% pore-forming agents of 5 μm diameter. The mixed power was die-pressed to specimens of $150 \times 15 \times 8 \times 120$ mm (outer diameter × rim width × thickness × length). The specimens were sintered in a tube furnace in an argon atmosphere. The specimens were heated to 250 °C and held for 30 min to eliminate humidity and air. Then, they were slowly heated to 450 °C, held for 60 min to allow for pyrolysis of the pore-forming agent, and then slowly heated to 625 °C and held for 30 min. Subsequently, they were directly heated to 730 °C, held for 90 min, and then furnace cooled to room temperature. After sintering, the 6A2 grinding wheel was prepared by attaching the sintered specimens to an aluminum alloy holder using an epoxy resin. The porosity of the grinding wheel used for the tests in this work was found to be in the range of approximately 35.5% to 43.2%, as determined by the method according to JB/T7999-1995 [13].

Grinding measurements for the grinding wheels were performed using a grinding PSIS.7 machine at a speed of 2200 rpm. A PCD blade was used for the grinding test. During the grinding process, the PCD blades were grinded one by one, the PCD blade was reciprocated, and the moving distance was set to 60 mm with a frequency of 80 time/min. The fracture surface and the grinded surface of the grinding wheel specimens were examined using a scanning electron microscope (SEM).

3. Results and discussion

3.1. Effect of porosity on the impact strength of vitrified bond grinding wheels

Fig. 1 shows the effect of porosity on the impact strength of vitrified bond grinding wheels. It can be observed that when the porosity of the vitrified bond grinding wheels is lower than 40.5%, the impact strength increases with the porosity. When the porosity increases to 40.5%, the highest impact strength is obtained. A further increase in the porosity will cause the impact strength to decrease. These results indicate that the addition of pore-forming agents to the wheel not only increases the porosity but also increases the impact strength of the vitrified bond grinding wheel. However, when the porosity increases to a sufficiently high value, the loading area decreases, causing the impact strength to decrease. These results indicate that an optimum porosity exists for the vitrified bond grinding wheel.

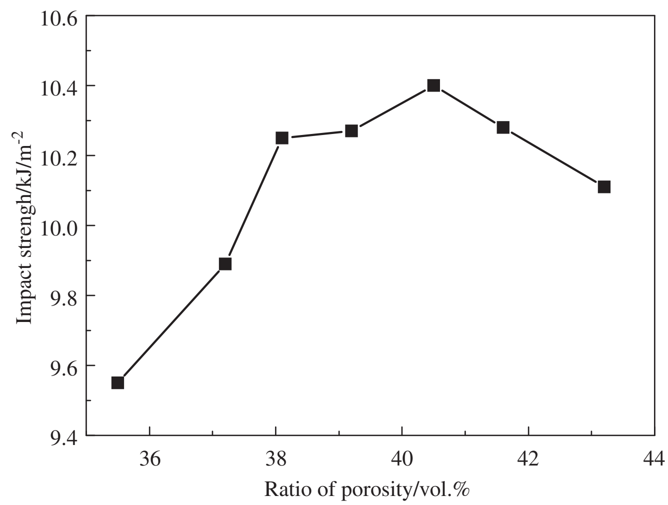

Fig. 1. Effect of porosity on the impact strength of vitrified bond grinding wheels.

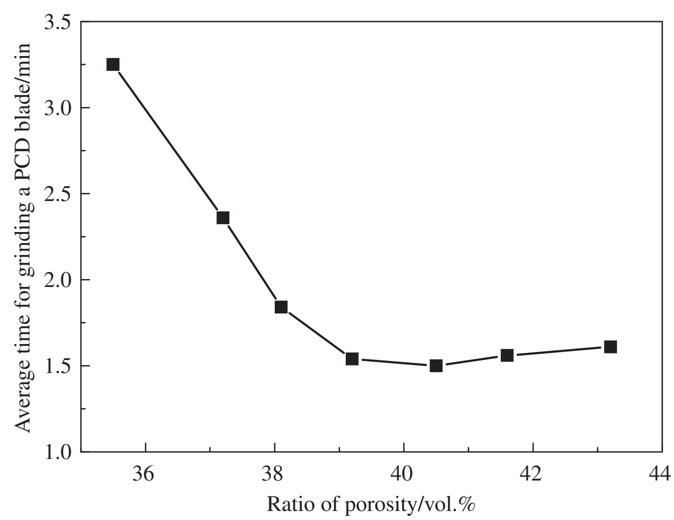

Fig. 2. Effect of porosity on the grinding efficiency of the wheels.

3.2. Effect of porosity on the grinding properties of vitrified bond grinding wheels

Fig. 2 shows the effect of porosity on the grinding efficiency of the wheels. When the porosity is lower than 40.5%, the average time to grind a PCD blade decreases remarkably with an increase in the porosity. When the porosity reaches 40.5%, the grinding time changes little with the porosity. As the porosity increases further, the grinding time begins to increase.

The porosity and the size of the pores not only affect the removal rate of the grinding chip but also affect the grinding surface and cooling because porosity is beneficial for grinding chip removal and coolant storage. Therefore, with an increase in the porosity, the removal rate of the grinding chips increases and the grinding surface is sufficiently cooled. However, the amount of effective abrasive in the wheel decreases with the increase in the porosity, which results in a decrease in the grinding efficiency. These results can be confirmed by the results of dressing time shown in Table 1. At a porosity of 35.5%, the wheel must be dressed to grind 3–5 PCD blades. If this is not done, the grinding surface of the PCD blade may burn. The dressing time, however, decreases with the increase in the wheel porosity. When the porosity exceeds 40.5%, the wheel demonstrates good self-dressing performance, and the dressing is not needed during the entire grinding process. However, when the porosity increases to 41.6%, the compressive strength of the wheels decreases, and some abrasive grains fall off of the grinding surface early. As a result, 3–5 dressing times are needed.

Fig. 3 shows the effects of the porosity on the service life of the wheels. It appears that the relationship between porosity and service life is similar to that between porosity and impact strength. When the porosity is lower than 40.5%, the number of grinded PCD blades increases remarkably with the increase in the porosity. Combining with the results in Table 1, for a wheel with low porosity, the wheel has a relatively low self-dressing and thus must be dressed repeatedly during grinding process, which results in high losses of the wheel during the dressing. Therefore, the service life of the wheel decreases.

The porosity of the wheels also affects the surface roughness of the grinded PCD blades, as observed in Fig. 4. The grinded PCD blades begin to have a low surface roughness when the porosity of wheels reaches approximately 40.5%.

From these results, we can conclude that the porosity of the vitrified bond grinding wheels affects many properties, including impact strength, grinding efficiency, self-dressing and service life, as well as the surface roughness of the grinded PCD blade. In addition, the porosity of the vitrified bond grinding wheels has an optimum value range.

Table 1
Dressing times of wheels during grinding process.

Wheels	Porosity (vol%)	Dressing times	Note
1	35.5	Each grinding 3–5 PCD blades	Surface burned
2	37.2	Each grinding 10 PCD blades	–
3	38.1	3–5 times in the grinding process	–
4	39.2	0 times	–
5	40.5	0 times	–
6	41.6	0 times	–
7	43.2	3–5 times in the grinding process	Low compressive strength

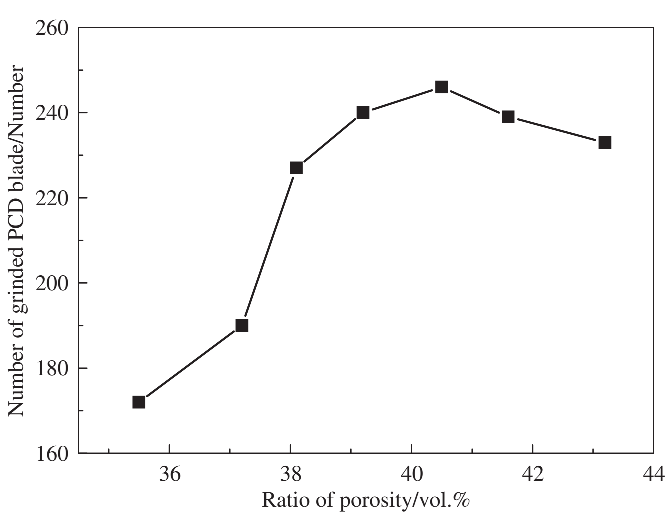

Fig. 3. Effect of porosity on the service life of the wheels.

3.3. Morphologies of the impact fracture and working surface of the wheels analyzed by SEM

Fig. 5 shows the SEM impact fracture morphologies of vitrified bond grinding wheels with different porosities. The vitrified bond grinding wheels without any pore-forming agents do present a porous microstructure, as some pores are observed in the SEM image (Fig. 5a). The size and distribution of the pores are non-uniform, and some small, close pores can be observed. From Fig. 5a, it can be observed that the crack propagates primarily along the vitrified bond bridge and that the diamond is packed closely by the vitrified bond. This result indicates that the nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond in this work results in good adhesion with the diamond.

Addition of the pore-forming agent in the wheel not only affects the porosity but also affects the size and

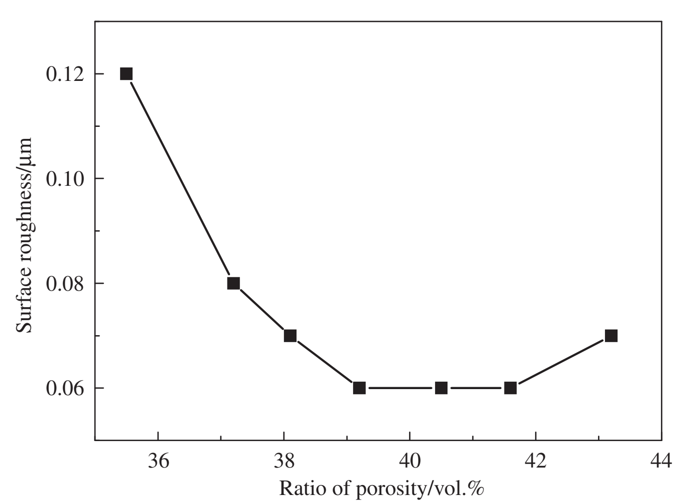

Fig. 4. Influence of porosity on the surface roughness of grinded PCD blades.

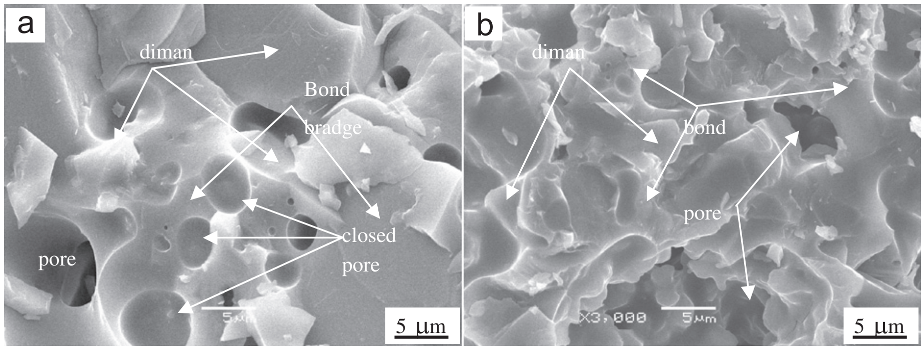

Fig. 5. SEM impact fracture morphologies of vitrified bond grinding wheels with different porosities (a) 35.5 vol% and (b) 40.5 vol%.

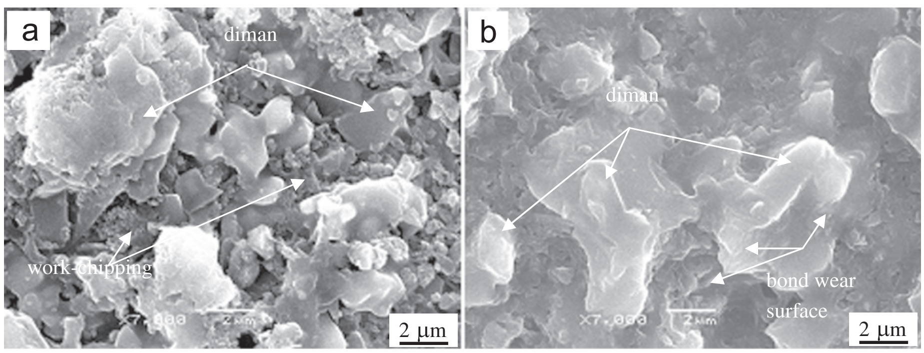

Fig. 6. SEM morphologies of the working surface of the wheels without any cleaning (a) 35.5 vol%; (b) 40.5 vol%.

distribution of the pores (Fig. 5b). As the porosity of the wheel increases, the size and distribution of the pores in the wheel become more uniform; moreover, the pores connect with one another. These characteristics of the pores can affect the porosity of the wheels, which is clearly illustrated in the SEM images of the grinding surface of the wheels without any cleaning (Fig. 6). When the porosity of the wheel is low, the grinding chips stack in the pores on the working surface. However, for a wheel with an optimum porosity, the grinding chip is hardly observed on the working surface. The diamond abrasive grains protrude from the working surface, but are firmly held by the vitrified bond. As a result, the wheel with the optimum porosity has sufficiently good self-dressing to obtain the highest grinding properties.

4. Discussion

The microstructural constituents of porous vitrified bond diamond wheels include primarily abrasive grains and vitrified bonds with pores. The compositions and microstructures of the bonds are the primary factors influencing the properties of bond bridges, the forces acting on the abrasive grains, and, ultimately, the properties of the wheels. Our previous work shows that the nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond has excellent characteristics to suit the manufacturing of diamond wheels due to its low thermal expansion coefficient and melting point, which reduces the surface tension at the bond bridge–abrasive grain interface, and the high interfacial bonding strength of the vitrified bond with the diamond grains [14]. However, for the results in this work, the bond and abrasive properties of the wheels are the same, but the impact strength and grinding properties of the wheels with different porosities exhibit notable differences (Figs. 1–4 and Table 1). These results indicate that the pore structure has a strong influence on the performance of the vitrified bond.

According to the results of the SEM analysis, the structure of the vitrified bond diamond wheel is porous. The pores come from three sources: (1) the gas generated by the chemical reaction during sintering, (2) the air remaining between the vitreous grains and abrasive particles, and (3) the addition of a pore-forming agent in the wheel. For the nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond wheels studied in this work, the bond was fritted in advance. In addition, the nano-AlN has no oxidizing action in argon and no gas is generated by the chemical reaction between pre-fitted glass, nano-AlN and diamond. Hence, the pores mainly come from the air remaining between the vitreous grains and abrasive particles when the vitreous grains and abrasive particles agglomerate together during sintering and the air remains between the bound bridges, becoming closed pores (Fig. 5).

The size and distribution of the pores is related to the granularity of the pre-fritted glass and die-pressed consistency. When a pore-forming agent is added to the wheel, the pore-forming agent will decompose during the sintering process. The pores generate in the locations where the pore-forming agent exists, thus the size, distribution and fraction of the pores strongly depends on the size, distribution and fraction of pore-forming agent particles in the die-pressed wheel [15]. The porosity can be accurately controlled by adding a pore-forming agent. In addition, as pore-forming agents decompose, gas is released into the wheel, causing the pores to connect with one another and forming a dimensional network of connected pores in the wheel. This network of pores greatly affects the properties of the wheel.

For this brittle vitreous material, the proper porosity in the wheel can arrest the crack propagation. For the samples without a pore-forming agent, the pores are in a closed state, and the pores do not effectively arrest crack propagation. Therefore, the impact strength of the wheel is low (Fig. 1). When the pore-forming agent is added to the wheel, a perfect pore network is formed in the wheels, which can effectively arrest crack propagation. Consequently, the impact strength of the wheel is improved (Fig. 1). Of course, when the porosity increases past a certain value, the impact strength of the wheel would decrease because of the decrease in the carrying load area.

During the grinding process, the properties of the vitrified bond wheels, such as grinding efficiency, dressing times, service life, and surface roughness of the work piece, depend not only on the microstructure and properties of the bond but also depend strongly on the porosity and structure of the pores in the wheel (Figs. 2–4 and Table 1). The grinding work process is also a tribological wear process, interaction of the bond with the work piece during motion leads to simultaneous tribological wear of both the grinding wheel and the work piece. This is due to gradual wear from the friction manifesting itself by continuously changing the dimensions of the wheel and work piece during the material removal process. During the grinding work process, the tribological wear state and the interface between the wheel and the work piece are very important factors affecting the grinding properties of the wheel because they strongly affect the work-chipping removal and cooling fluid concentration on the wear surface.

In this work, the porosity is a very important factor that affects the wear surface characteristics. If the porosity of the wheel is low, the closed pores in the wheel are separated from each other by bond bridges and abrasive gains in the wear surface, which restricts the removal of work-chippings and the flow of the cooling fluids. The chips then stack in the pores (Fig. 6), causing the frictional force to increase and the cooling effect to decrease. Consequently, the grinding efficiency of the wheel then decreases. In addition, the work-chippings on the grinding surface function as abrasive particles and wear down the grinded surface of the work piece, resulting in an increase in the roughness of the work pieces.

As the porosity of the wheel increases to an optimum value, the pores begin to represent a dimensional network structure, and channels of connected pores begin to form in the working surface of wheel. These channels are beneficial for the removal of work-chippings and the flow of coolant, and, consequently, cause the frictional force to decreases to the lowest level. This decrease in friction forces is due to the lubrication action of the cooling fluid and the highest work-chippings removal rate. Therefore, the grinding properties of wheel, including grinding efficiency, dressing time, service life, and surface roughness of the work piece, are improved.

5. Conclusions

(1) The grinding properties of nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond diamond wheels for grinding PCD work pieces can be improved greatly by adding a suitable fraction of a pore-forming agent to obtain optimum porosity in wheels. The optimum porosity of the nano-AlN modified Na_2O–B_2O_3–SiO_2 vitrified bond diamond wheel for grinding PCD tools is approximately 40.5 vol% in this work.

(2) With an increase in the porosity, the pores connect with each other, forming a perfect network of pores in the wheels, which can efficiently arrest crack propagation, accelerate the removal of the chippings, and aid cooling fluid flow on the abrasive surface. Furthermore, the impact strength, grinding efficiency, self-dressing, service life of the wheels and the surface roughness of the work pieces are improved with an increase in the porosity up to a certain point. When the porosity becomes too high, the carrying load area decreases and the early fracture of bond bridges arises during the grinding process, leading to a decline in the grinding properties of the wheels.

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