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Raw materials selection applied to glass bonding for vitrified CBN grinding wheels

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Abstract In this article the selection of more appropriate raw materials applied to alumino-borosilicate glass system for vitrified cubic boron nitride (CBN) grinding wheels was investigated. The selection of raw materials had a major effect on the performance of specimens. Mechanical properties of the specimens were measured by using three-point bending strength tester and microstructure characteristics of specimens were examined by scanning electron microscopy (SEM). The results showed that the elements barium and magnesium in the form of carbonate were more beneficial to the refractoriness and fluidity of glass binder than in the form of hydrate and oxide. Moreover, the element barium in the form of carbonate was more favorable to mechanical property of glass binder than that in form of hydroxide. But magnesium carbonate was harmful to improve the mechanical property of glass binder. Therefore, selection of appropriate raw materials used in glass binder was dependent on their natural characteristic.

Introduction

Owing to the excellent mechanical properties, CBN grinding wheels are becoming one of the most potential tools in modern engineering applications [1–3]. However, there are still challenges to realize the advantages of CBN grinding in industry [4]. Optimal CBN grinding requires a systematic approach taking account of all relevant factors [5].

Vitrified bonded CBN wheels are typically used for high performance grinding processes, and in comparison with other types of bonds, vitrified bonds permit easy dressing while at the same time possessing high levels of resistance to wear [6, 7]. This is because CBN wheels are designed to have a lower wear rate and it is important that the grains are not easily lost by breaking away from the bond. Therefore, the properties of the vitrified bond and the interface between the bonding bridges and the abrasive grains were very important. If the vitrified bond had low joining strength to grains, in some cases the CBN superabrasive grains were easily pulled out and lost before completing their effective working life, which led to excessive tool costs. Therefore, in recent years more and more attentions were paid to research the performance of vitrified CBN grinding wheels [5, 6, 8–12]. Nevertheless, referring to glass binders and new technologies of bonding the abrasive grains into the tool, there are few works published in comparison with other branches of science (legal protection for manufactures of new designs). Only a few publications are available, which contribute some ideas to composition of the binders [13–17].

T. I. Barry et al. [13] had reported the composition of glass bonds using for vitrified alumina grinding wheels, the bonds were composed of mixtures of laboratory grade oxides or carbonates. The results of experiments using vitreous bonds showed that good flow characteristics were needed. In Poland, the study related to alumino-borosilicate glasses as vitrified binders for superhard grinding tools had been reported [14]. In other studies, M. J. Jackson et al. [15–17] had studied the effect of bond composition on the properties of vitrified abrasive materials. The raw materials of bonds used were quartz, feldspar, clay, borate minerals, ground frits, and others. Although some studies were paid to research the glass as binders for vitrified CBN grinding

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wheels, the previous studies did not pay much attention to the raw materials selection applied to glass bonding for vitrified CBN grinding wheels. Under such conditions, it is very urgent and important to research the influence of raw materials selection on the performance of vitrified bond.

The raw materials added to the alumino-borosilicate glass bonding system (i.e., $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$, MgO and $MgCO_3$), inspite of containing same components after sintering, may have different effects on the property of the bond. Therefore, in the present study, an attempt has been made to explore the influence of raw materials on the properties of glass bonding system with different BaO and MgO contents for the first time.

Experimental

Alumino-borosilicate glass was used as a basic bonding system for vitrified CBN grinding wheels. The basic glass binder was obtained from a pre-calcination process, and all the glass specimens were prepared by adding different materials. The basic bonding system introduced barium components in the form of $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$ individually, to which was added either 3% or 5% barium (all by weight). In addition, the matrix added magnesium components in the form of MgO and $MgCO_3$, respectively, to which was added either 3% or 5% magnesium (all by weight). Then ball milling was done for 24 h in a polyethylene jar to achieve uniform mixing. After sieving, the glass binders with the above additives were uniaxially pressed into tapered columns and cylinders, which were sintered in an electric furnace used for measuring refractoriness and fluidity.

Specimens were prepared by mixing with CBN grains, glass binders, and temporary binders, then the powder was molded into rectangular bars (30 mm × 6 mm × 4 mm). The obtained compacts were heated to the sintering temperature at the rate of 5 °C/min, up to the sintering temperature for 2 h, and then naturally cooled to the room temperature. Bending strength was measured using three-point bending method according to C158 ASTM in MTS machine at a cross-head speed of 0.6 mm/min. The average value was obtained from measurement of five samples. The microstructures of the fracture surfaces of sintered specimens were evaluated by scanning electron microscope (Phillips XL30).

The performance index used to characterize wheel wear resistance is the grinding ratio, or G-ratio, and is expressed as the ratio of the change in volume of the workpiece ground to the change in the volume of the grinding wheel removed, thus,

$$G = \frac{\Delta v_w}{\Delta v_s} \tag{1}$$

where G is grinding ratio, Δv_w the workpiece removed volume, Δv_s the wheel worn volume.

Table 1 Grinding experimental conditions

Grinding machine	High-speed surface-grinding machine: MS1320
Grinding wheel	CBN 140/170 P 125 VN1 1A1 400 × 10 × 127 3.0x
Truing	Traverse cutting of an electroplated diamond disc
Dressing	Abrasive stick (WA220 G) 7.2×10^3 mm^3/pass
Workpiece	SKD11(A typical mold steel of HRc58) Φ120 × 8 × Φ40
Coolant	Mineral oil (1×10^6 mm^3/min)
Grinding speed v_s	50 m/s
Workpiece speed v_w	12 mm/s
Depth of cut	25 μm

Grinding ratio measurement of the vitrified CBN grinding wheels was performed using a surface-grinding machine (MS1320). A typical mold steel (SKD11) of HRc 58 was used for grinding ratio test, and the grinding conditions were shown in Table 1. The work surface was roughly ground for preparation. Before the test run, CBN wheel was properly trued and dressed.

Results and discussion

Refractoriness studies

The elements barium and magnesium were introduced into the basic alumino-borosilicate glass bonding system with various raw materials and different contents. Barium was imported by $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$, respectively, and magnesium was obtained from MgO and $MgCO_3$. In order to evaluate the proper sintering temperature of the grinding tools were composed of CBN abrasives and these binders, the refractoriness of these binders were examined. Figure 1 showed the refractoriness of the alumino-borosilicate glass bonding system with addition of $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$. It was clear that the refractoriness was decreased by introducing barium, the binders with addition of $Ba(OH)_2 \cdot 8H_2O$ had higher refractoriness than that with introducing $BaCO_3$. No matter whether $Ba(OH)_2 \cdot 8H_2O$ or $BaCO_3$ was imported, the refractoriness reduced with increasing of BaO content. The alkaline-earth element Ba acts as a network modifier in the silica glass [18], which dissolved in the liquid-like network when extra O^{2-} ions dangle off of the network. Consequently, the metal ions were added to the glass network leading to the reducing of glass-fused temperature.

Figure 2 showed the refractoriness of the base binders with introducing MgO and $MgCO_3$. There was also some indication that the binders containing magnesium

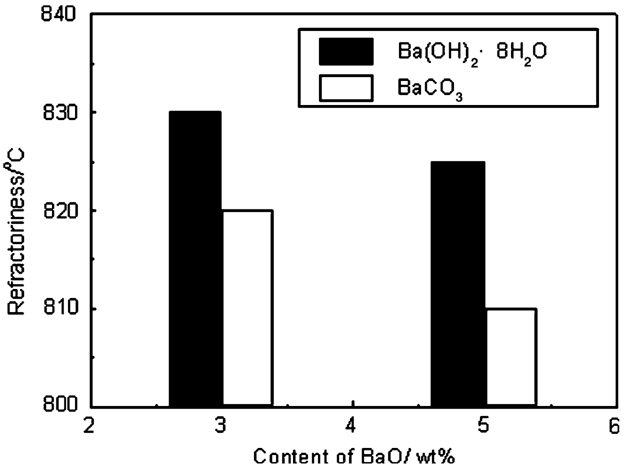

Fig. 1 Refractoriness of glass binders with import of $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$

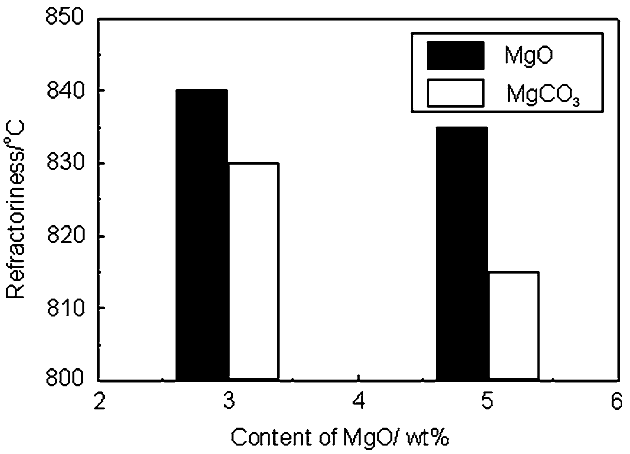

Fig. 2 Refractoriness of glass binders with import of MgO and $MgCO_3$

component in the form of $MgCO_3$, as opposed to intermingling with magnesium component in form of MgO, had lower refractoriness. $MgCO_3$ was decomposed during heat treatment, which led to yielded magnesium oxide with higher chemic active and lower fused temperature. Therefore, lower refractoriness was obtained by introducing $MgCO_3$ than direct import of MgO.

Fluidity analysis

In several research studies it had been demonstrated that glass-type binders prove to be strong abrasive tools. This was due to their very high fluidity which favors the formation of stronger bond bridges between abrasive grains. From the presented investigations, it follows that these glass binders had high fluidity. Figure 3 showed the fluidity of glass binder with addition of $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$ at the same sintering temperature. Moreover, the fluidity of glass binder with addition of MgO and $MgCO_3$ sintering at the same temperature was shown in Fig. 4. It was clear that fluidity was correlative with refractoriness. The glass binder with lower refractoriness had higher fluidity. As shown in Figs. 3, 4, higher fluidity was observed with introducing carbonate than hydrate and oxide. It was believed that the difference of fluidity might be responsible for the different decomposition in the heat treatment, because barium hydroxide absorbed CO_2 in air and turned to barium carbonate firstly, and then decomposed to barium oxide in the sintering process. Moreover, Mg^{2+}, Ba^{2+} ions act as network modifiers, inducing non-bridging oxygens, and lie in interspaces of the glass network, then break up the glass network at lower temperature, thus higher fluidity was obtained. However, the effect of Ba^{2+} ions on the increasing of fluidity was higher than Mg^{2+} ions. This was due to the bigger ionic radius of Ba^{2+} ions than that of Mg^{2+} ions.

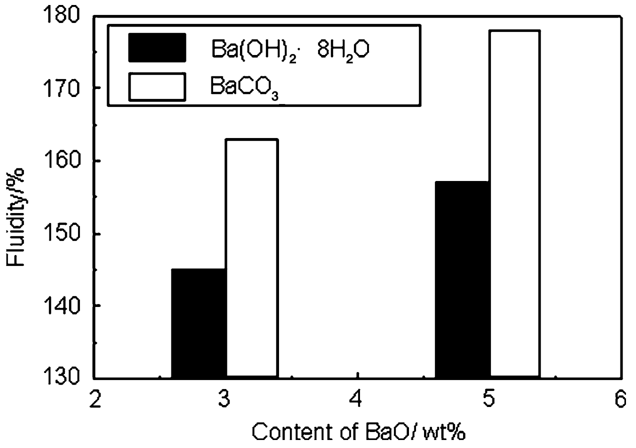

Fig. 3 The fluidity of glass binders with import of $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$

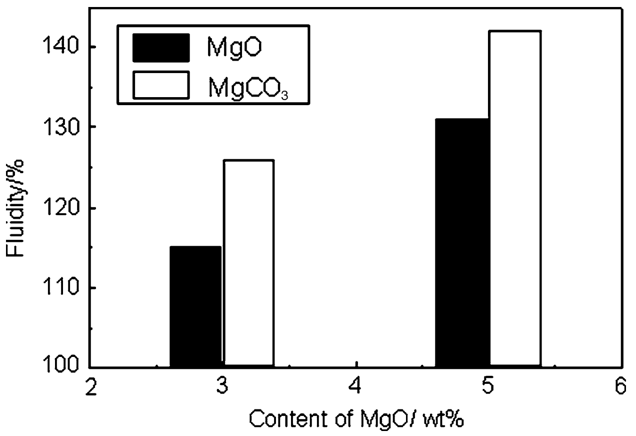

Fig. 4 The fluidity of glass binders with import of MgO and $MgCO_3$

Mechanical property

In this study, the bend strength of the specimen bars with different glass binders sintering at different temperatures is shown in Figs. 5, 6. The bend strength was distinctly influenced by the different raw materials. From Fig. 5a, b, it can be seen that these curves had similar changing tendency, the bend strength increased with increasing of the sintering temperature when it was below 880 °C, and with continued increasing of temperature the bend strength was decreased. Comparison of the results of bend strength, the specimen with 3 wt.% BaO in the form of $BaCO_3$ had the highest bend strength at the sintering temperature of 880 °C, it was about 85 MPa. In generally, it can also be seen that the specimens with import of $BaCO_3$ had higher bend strength than the specimens with addition of $Ba(OH)_2 \cdot 8H_2O$, when the content of barium oxide was 3 wt.% and 5 wt.%. This may be due to the different reactions in heat treatment processing. When $Ba(OH)_2 \cdot 8H_2O$ was heated it partly absorbed CO_2 in air and turned to $BaCO_3$ and H_2O, then $BaCO_3$ broke down into BaO and CO_2. These reaction processes consume more energy than direct decomposition of $BaCO_3$. And finally, as opposed to direct decomposition of $BaCO_3$, more gas formed. The existent H_2O was harmful to the uniformity and density of the specimens.

According to the refractoriness and fluidity analysis of the specimens by introducing MgO and $MgCO_3$, it was shown that the specimens by introducing $MgCO_3$ had lower refractoriness and higher fluidity than those introducing MgO. And the samples containing $MgCO_3$ had lower bend strengths than those containing MgO. This occurred because $MgCO_3$ decomposed at the temperature between 800 °C and 900 °C. At the same time carbon dioxide gas was formed during $MgCO_3$ decomposition. With increasing sintering temperature the fluidity of binders increased, and the viscosity reduced. The decrease in viscosity allowed gas formed from the breakdown of magnesium carbonate to be encapsulated in the glass network and coalesce with other gas bubbles to form large

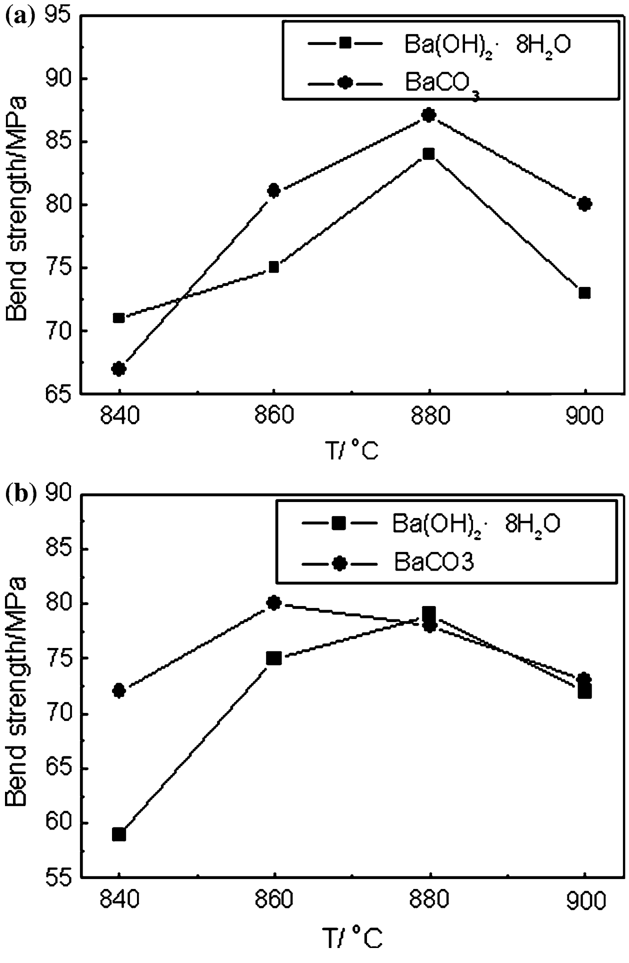

Fig. 5 The bend strength of specimens with import of $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$ (**a**) 3 wt% BaO; (**b**) 5 wt% BaO

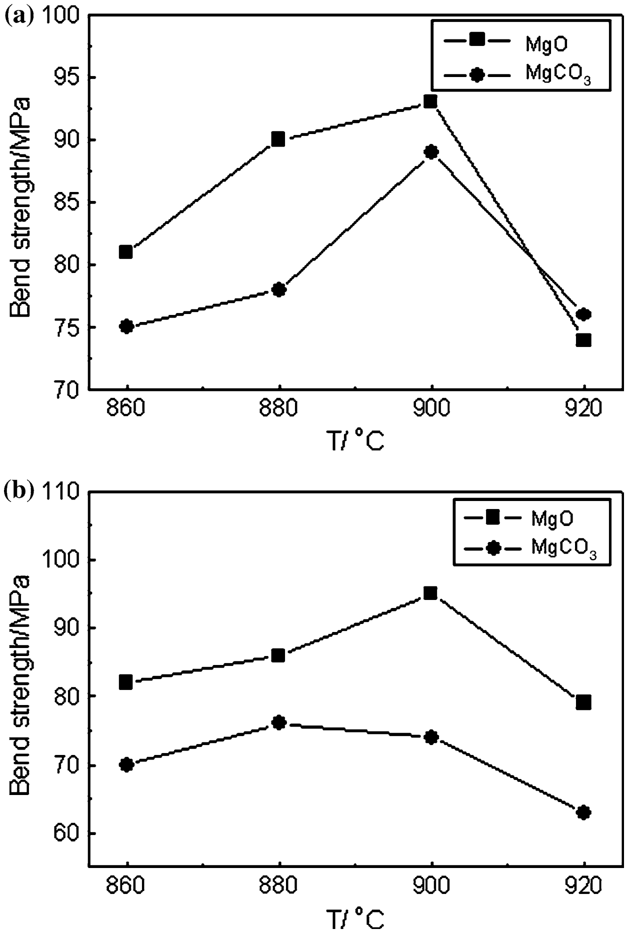

Fig. 6 The bend strength of specimens with import of MgO and $MgCO_3$ (**a**) 3 wt% MgO; (**b**) 5 wt% MgO

pores. Therefore, many gas bubbles were formed in the glass, it resulted in the high porosity in glass bonding bridges and the decrease of the bend strength.

Microstructure analysis

Some attempts to study fracture surfaces microstructure of specimens were made using scanning electron microscopy. Figure 7a, b showed fracture surfaces of the specimens with 3 wt.% barium oxide content, which was introduced by $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$, respectively. It was obvious that both of these two binders wetted perfectly the abrasive grains and formed regular bond bridges fixing the abrasive. But there was also a great difference in microstructure. The sample with addition of $BaCO_3$ (Fig. 7a) had denser structure compared to that with addition of $Ba(OH)_2 \cdot 8H_2O$ (Fig. 7b). When barium oxide was imported by $Ba(OH)_2 \cdot 8H_2O$, many pores and narrow glass bonding bridges were observed in the specimen, because more gases (H_2O and CO_2) formed from the breakdown of $Ba(OH)_2 \cdot 8H_2O$ than decomposition of $BaCO_3$, this composite morphology indicated the decrease of bend strength.

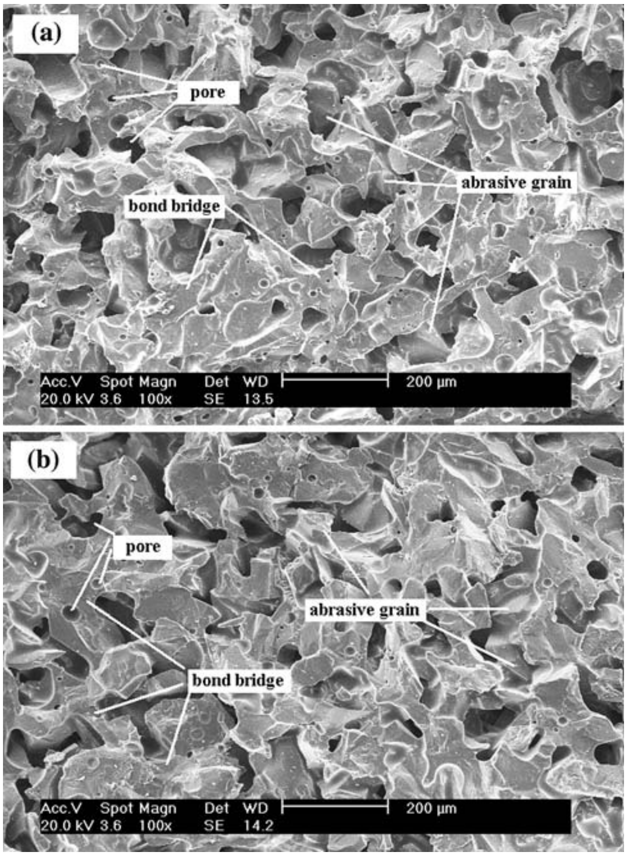

Fig. 7 Fracture surface images of samples with addition of $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$ (**a**) Introducing $Ba(OH)_2 \cdot 8H_2O$; (**b**) Introducing $BaCO_3$

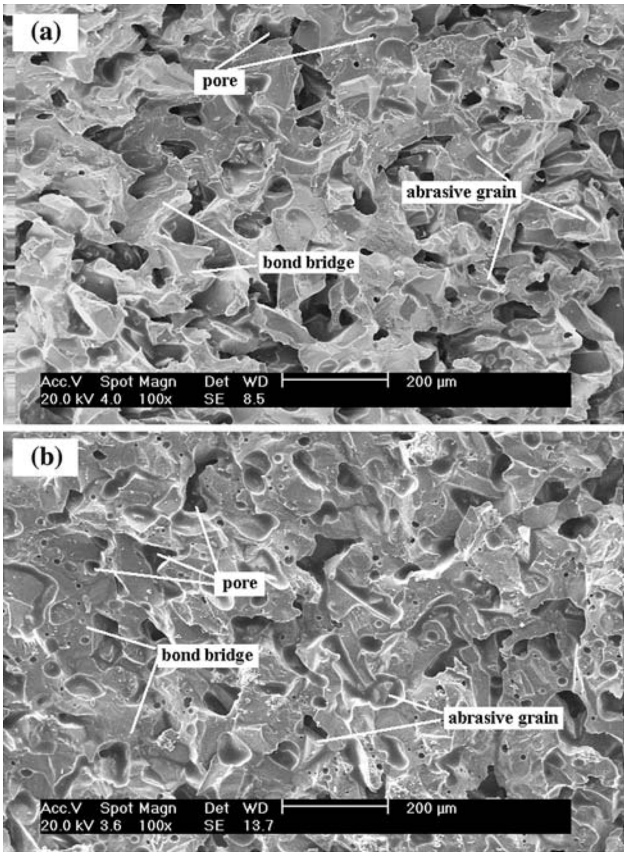

Fig. 8 Fracture surface images of samples with addition of MgO and $MgCO_3$ (**a**) Introducing MgO; (**b**) Introducing $MgCO_3$

Figure 8 showed micrographs of specimens with addition of MgO and $MgCO_3$. It can be seen that abrasive grains bonded together by these two kinds of glass binders. Comparing with Fig. 8a, b, it was found that there was an obvious difference in microstructure. When magnesium oxide component was imported by $MgCO_3$, many pores were obtained in the bond bridges, because CO_2 gas formed from the breakdown of magnesium carbonate did not completely escape from the glass binder. On the contrary, when it was imported by MgO, compact bond bridges were obtained. Therefore, the samples with addition of $MgCO_3$ had lower bend strength than that with addition of MgO. The result lent evidence to support the conclusion of the mechanical property.

Grinding ratio

To evaluate the effect of different vitrified bonds on the grinding ratio of CBN grinding wheels, the grinding experiment was carried out on a high-speed surface-grinding machine. For the basic glass binder of grinding wheels, barium was imported by $Ba(OH)_2 \cdot 8H_2O$ and $BaCO_3$, respectively. And magnesium was obtained from

MgO and $MgCO_3$. Table 2 showed the grinding test values for different vitrified bonds CBN grinding wheels. It was found that the grinding ratios of all the CBN grinding wheels were greater than 2,342 when the workpiece removed volume was about 800,000 mm^3. The wheel with barium in the form of $BaCO_3$ had higher G-ratio than that with barium in the form of $Ba(OH)_2 \cdot 8H_2O$, but the specimen with introducing $MgCO_3$ had lower G-ratio than that with introducing MgO. Moreover, the CBN grinding wheel with the glass binder-added MgO had the highest grinding ratio ($G = 2{,}694$). From the analyses of mechanical property, microstructure, and grinding ratio, the results indicated that the highest bend strength, or the highest sintered density yielded the highest G-ratio.

Table 2 Grinding test values for different CBN grinding wheels

CBN grinding wheel type*	Removed volume of workpiece $\Delta V_w/mm^3$	Radial wear extent of wheel $\Delta r_s/\mu m$**	G-ratio
A	836,140	36.4	2,342
B	804,469	33.1	2,498
C	816,391	30.8	2,694
D	829,357	33.2	2,560

* A, B, C, and D were different types of vitrified CBN grinding wheels, which their glass binders with addition of $Ba(OH)_2 \cdot 8H_2O$, $BaCO_3$, MgO, and $MgCO_3$, respectively

** The radial wear extent was average value of random ten points on the wheel surface measuring by outside micrometer

Conclusions

Selection of the more appropriate raw materials applied to alumino-borosilicate glass bonding system for binding CBN abrasive grains into grinding wheels was investigated. In this study, raw materials of hydrate, carbonate and oxide were chosen to make a series of experiments. As described in this article, the glass binder with addition of carbonate had lower refractoriness and higher fluidity than the glass with addition of hydrate and oxide, which was beneficial to improve the performance of the glass binder applied to the CBN grinding wheels. When the added component was imported by carbonate which its decomposition temperature was higher than the sintering temperatures of the grinding tool specimens, the glass binder with addition of carbonate had higher mechanical strength and grinding ratio than that with addition of hydrate. For introducing Ba content, the decomposed temperature of barium carbonate was much higher than sintering temperature of the specimens. Consequently, the binder-added barium component in form of $BaCO_3$ was better than that in the form of $Ba(OH)_2 \cdot 8H_2O$. However, when the added component was imported by carbonate which its decomposition temperature was among the sintering temperatures of the grinding tool specimens, many gas bubbles were formed in the glass bond bridges, and resulted in decrease of the mechanical strength. For example, the specimens with addition of magnesium carbonate had lower bend strength and grinding ratio than that with addition of magnesium oxide. Based on the above result, it was shown that selection of appropriate raw materials used in glass binder was dependent on their natural characteristic.

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