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INVESTIGATION OF MACHINING PROCESSES

Investigation of Performance of Tools with Reduced cBN Concentration in Grinding Hardened Steels

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Abstract—Grinding wheels of cubic boron nitride in vitrified bonds, with a grain content varying from 25 to 12.5 vol % in the tool working layer (100 and 50% concentration, respectively), have been developed and tested. In internal grinding of bushings of hardened steels the wheels with a reduced cubic boron nitride concentration have been found to provide a higher machining efficiency and about 2.5-times lower specific abrasive consumption in comparison to tools with 100% concentration.

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1. INTRODUCTION

The structure of grinding wheels of aluminum oxide and silicon carbide is an important tool performance parameter. As the structure number is lowered with an accompanying reduction of volumetric content of the abrasive in the tool, the grinding forces and temperatures decrease and so does the abrasive consumption. The favorable thermodynamics of the material removal process facilitates the formation of the workpiece surface layer with minimum cold work hardening and residual compressive stresses, thus resulting in better performance of the machined parts [1–3].

For example, in grinding hard-magnetic materials the increase of the structure number from 10 to 14 for aluminum oxide wheels has more than halved the cutting force components. In creep feed grinding of roots of turbine blade of high-temperature nickel alloys the increase of the structure number has provided a rise of machining efficiency up to 2.7 times and an 2.5-fold reduction of abrasive costs. In machining with a wheel having the 12th structure the grinding temperature in machining nickel alloys and hardened steels decreases by 300–400 degrees if compared to a wheel with the 5th structure [4, 5].

The effectiveness of using high-structure abrasive tools is not only due to the reduced grain content but also to the related increase of porosity. The bulk and surface porosity becomes one more factor for improving performance of high-structure tools, for it contributes to cooling the cutting zone and handling the chips, thus preventing “loading” of the tool working surface.

Successful practice of reducing volumetric concentration of cubic boron nitride (cBN) from 25 to 15% was reported in [6], where we described the results of development and testing tools in vitrified bonds for efficient dry grinding. Tools with a reduced cBN concentration has enabled us to implement the plunge-cut grinding process that simulates machining of automobile engine camshaft lobes of hardened steel, with power consumption up to 30% lower in comparison with abundantly wet grinding.

In this publication we will consider the results of elaboration and application of cubic boron nitride tools with a reduced cBN concentration for top-priority and most widely used wet grinding operations for hardened steel workpieces.

Successful solution of the problem of development of these tools will undoubtedly facilitate extending the range of their efficient application in profile grading of intricately shaped workpieces, such as gears, broach tools, blades for turbines and compressors, and so on. For these processes an important task is to provide cost-effective and fast truing of cBN wheels using diamond rollers, considering that this operation usually takes as long as two and more hours and accounts for up to 70% of the total grinding costs.

2. EXPERIMENTAL

We have developed and manufactured grinding wheels of high-strength cubic boron nitride (LKV) of Elbor trademark, of V151 (160/125) grain size, in K27 vitrified bond. The proposed tool compositions for the machining tests, which contained 25 to 12.5 vol % cBN, are based on the ideas and recommendations given in [7, 8].

For technological purposes, a filler in the form of silicon carbide or aluminum oxide grains in the amount close to the cBN content, is usually added to the tool working layer to make up a composition cBN–abrasive filler–vitrified bond. To reduce the contribution of the abrasive filler to grinding, the filler grain size is recommended to be significantly decreased—it should be 4 to 6 numbers lower than the cBN grain size.

For the purpose of reducing concentration and thus increasing porosity of the cBN wheel working layer, various pore-forming additives were introduced therein; they included burnable substances (milled fruit pits) and non-burnable ones, such as alumina-silicate microspheres.

For the machining tests we prepared 1A1 50 × 8 × 16 wheels with a working layer thickness of 5 mm. The wheel body was made up of a mixture of an 24A-grade white fused alumina of grain size F180 and 63C-grade green silicon carbide of grain size F150 in the bond K27. The process of wheel manufacture was identical for all compositions and corresponded to that generally used for making cBN wheels in vitrified bonds.

Hardness of the sintered working layer was measured using a Rockwell hardness tester with a ball intender as per National Standards GOST R 52587–2006 and GOST R 53923–2010 (ISO 22917 : 2004).

We studied six cBN compositions, including the standard one in a reference wheel. The calculated porosity of the wheels was increased from 47% in the reference wheel with the 100% concentration to 58% in new tools. The degree of hardness of the proposed wheels was M, while that of the reference wheel was at the boundary N–O (HRC 44).

Table 1 shows the main constituents and hardness of the working layer of the proposed wheels and the reference cBN wheel (item 1). It follows from the tabulated data that as the cBN concentration is reduced the working layer hardness decreases. In this case, the decrease of hardness correlates with the increase of hardness of the wheel working layer: with increasing volumetric pore content up to 23% the average hardness of the samples decreased by almost 50%.

This decrease of hardness was observed at a larger bond content and thus a larger porosity (see the table). This finding is a further evidence of the influence of porosity on hardness of the tool working layer.

Composition of cBN grinding wheels, cBN concentration and hardness of the wheel working layer

No.	Content, vol %			cBN concentration, %	Hardness HRC
	cBN	bond	pores		
1	25.0	6.5	47	100	44
2	18.75	7.0	56	75	32
3	18.75	8.0	58	75	24
4	15.0	8.0	55	60	30
5	12.5	7.0	55	50	29
6	12.5	8.0	54	50	33

The applicable standards for hardness measurements take into account the relation between the tester readings and the abrasive grain size only, disregarding any effects of the cBN concentration and bond porosity. Therefore, the revealed correlation between hardness and porosity is a factor of their indirect influence on performance of the grinding wheels with a reduced cBN concentration.

The testing of the proposed high-porosity cBN wheels was performed by internal grinding on a Mod. TST 250-4R machine tool (Tripet, Switzerland). The bushings to be ground were made of steel KhVG (HRC 60) and had the following geometry: OD = 120 mm, width = 24.8 mm, and initial ID = 56.3 mm. The workpiece were fixed in a special arbor on the grinder spindle. Machining was performed by the pendular grinding mode with oil emulsion cooling under constant conditions: wheel speed = 30 m/s, workpiece rotational speed = 25 m/min, speed of the wheel longitudinal travel = 400 mm/min. The tool performance characteristics were measured at two values of the depth of cut per wheel stroke: 0.002 and 0.005 mm.

A stock of 1 mm per diameter was removed from each bushing by a wheel of one specification at a constant depth of cut. The stock removal time during the test was 15.5 and 6.2 min at a depth of cut of 0.002 and 0.005 mm, respectively. For each wheel the test was repeated three times.

Prior to grinding the wheels were dressed by a diamond roller with a rotational speed of 20 m/min and speed of longitudinal travel of 600 mm/min in two passes.

During the tests the ring inner diameter was measured using a Mod. Imicro Tesa type 61.30011B internal calipers with digital indication. The grinding wheel diameter was measured along two mutually perpendicular directions using a micrometer gauge with an 1 μm graduation mark and determined as an average of two values [9].

The workpiece ID surface roughness upon grinding was measured by a Mod. Mitutoyo SJ-201 portable device.

The tool performance was assessed by the variations of material removal rate Q_w (mm^3/min) and wheel working layer wear rate Q_s (mm^3/min), specific cBN consumption q (mg/g), and machined surface roughness parameter Ra (μm).

The quantitative assessment of the performance characteristics of the proposed cBN-based abrasive—ceramic composites was performed as per the established procedure taking into account the recommendations regarding the determination of the specific consumption q [8, 10]. The parameters Q_w, Q_s, and q were calculated based on changes of the actual inner of the workpiece and outer diameter of the wheel, accurate to 1 μm.

The test data were statistically treated by following the recommendations [11, 12], and the results of the correlation and regression analyses were used for explaining the revealed patterns and plotting the diagrams. The regression bond models were obtained in the form of nonlinear logarithmic polynomials for revealing possible extremums.

3. RESULTS AND DISCUSSION

Figure 1 shows the material removal rate Q_w vs. the volumetric cBN content of the wheel working layer for two values of the depth of cut (0.002 and 0.005 mm), with all other grinding conditions being constant. In both cases, we have noted a general pattern of variation of Q_w as a function of the cBN content V_z, with extreme values of the removal rate at $V_z = 15\%$ (i.e., at the 60% concentration).

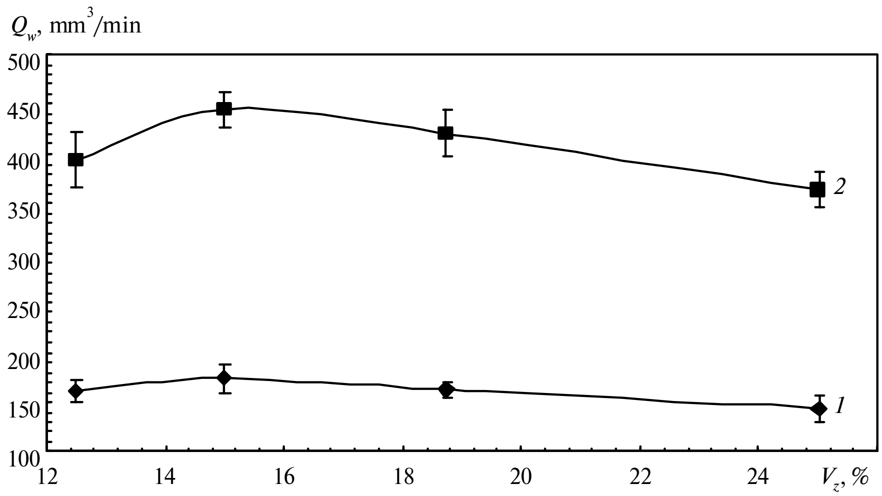

Fig. 1. The influence of the volumetric cBN content of the wheel working layer on the material removal rate at a depth of cut of 0.002 (*1*) and 0.005 mm (*2*).

The difference between the maximum and minimum values of Q_w with $V_z = 25\%$ (the 100% concentration) at two values of the depth of cut is almost equal and is 21% at $t = 0.002$ mm and 22% at $t = 0.005$ mm.

Upon assessment of the wheel wear rate we have also revealed the extremal relation between Q_s and relative cBN content of the tool working layer (Fig. 2). In grinding with a depth of cut of 0.002 mm the minimum wear rate of 0.27 mm^3/min was noted for the wheel with the 100% concentration of cBN and was 1.44 times lower than that of the wheel with $V_z = 15\%$.

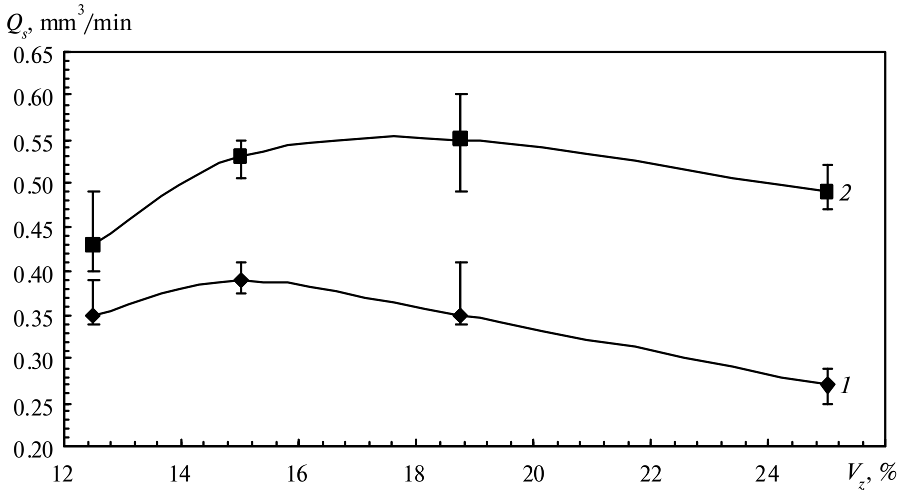

Fig. 2. The influence of the volumetric cBN content of the wheel working layer on the wheel wear rate at a depth of cut of 0.002 (*1*) and 0.005 mm (*2*).

As the depth of cut was raised from 0.002 mm to 0.005 mm or 2.5-fold, the average removal rate for six wheel specifications studied increased from 161.9 to 393.6 mm^3/min or by a factor of 2.43 and the average wheel wear rate grew from 0.34 to 0.445 mm^3/min (by 30%).

Due to the noted difference between the values of Q_w and Q_s their ratio, in view of the reduced cBN concentration in the wheels tested, has caused the pattern of $q(V_z)$ as shown in Fig. 3. The specific cBN consumption at a depth of cut 0.005 mm for all wheels has turned out to be at an average 1.64 times lower than that in machining with $t = 0.002$ mm.

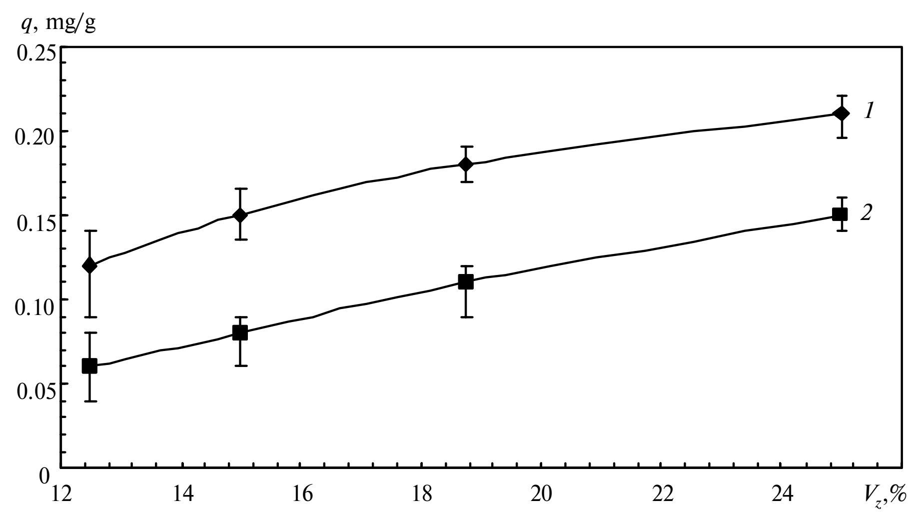

Fig. 3. The influence of the volumetric cBN content of the wheel working layer on the specific cBN consumption at a depth of cut of 0.002 (*1*) and 0.005 mm (*2*).

The trend of the influence of V_z is the same for both grinding cases: as the relative cBN content of the tool working layer is lowered, the specific cBN consumption decreases proportionally. With the cBN concentration reduced from 100 to 50%, the specific cBN consumption in grinding with a depth of cut of 0.002 mm decreases from 0.21 to 0.12 mg/g or by 75%, while in case of $t = 0.005$ mm it goes down from 0.15 to 0.06 mg/g or 2.5-fold.

Figure 4 illustrates the influence of the volumetric cBN content of the tool working layer on the machined surface roughness. The best results in terms of the parameter *Ra*—within 0.27–0.3 μm—were demonstrated by the reference wheel with the 100% cBN concentration. With a lower concentration the machined surface roughness parameter grows to 0.65–0.95 μm upon grinding with $t = 0.005$ mm.

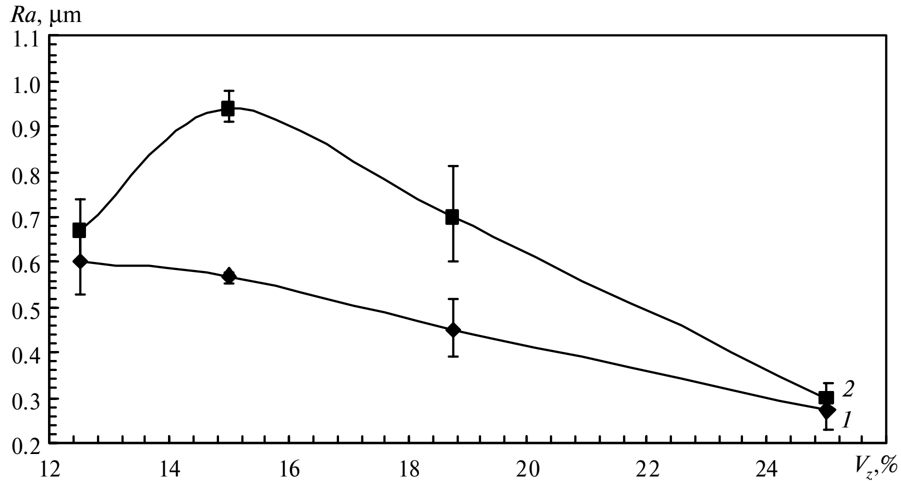

Fig. 4. The influence of the volumetric cBN content of the wheel working layer on the machined surface roughness at a depth of cut of 0.002 (*1*) and 0.005 mm (*2*).

According to the technical specification the machined bushing of steel KhVG which was used a workpiece in these tests is required to have a surface roughness parameter $Ra \leq 0.63$ μm. It is provided by finish grinding with a depth of cut of 0.002 mm using any of the wheels tested.

When analyzing the present findings, noteworthy is the following thing. During the investigations we could expect the tool performance to be influenced not only by the main wheel parameter V_z, which was varied between 125 and 25%, bu also by the wheel hardness. Its value ranged from HRC 44 for the reference sample with $V_z = 25\%$ to the minimum value of HRC 24 for the wheel with $V_z = 18.75\%$ which showed a good performance during the tests.

As per the National Standard GOST 53929–2010, all the five wheel compositions proposed and studied (except for the reference one) corresponds to the same degree of hardness—M (HRC 21–32). On the other hand, hardness as a specification parameter of an abrasive tool is known to have a great effect on the tool performance and especially on wear intensity.

The five tested wheels a reduced cBN concentration in the working layer had their Rockwell hardness ranging from HRC 24 to 33, and its average value was 1.38 times lower than that of the reference wheel with the 100% concentration. Therefore, just as expected, the grinding performance will be influenced by the wheel hardness as well as by the volumetric cBN content. This is indirectly confirmed by the significant spread of the test results as shown in Figs. 1 through 4 for the wheels with the volumetric cBN content of 12.5 and 18.75 (the 50 and 75% concentrations, respectively) and different values of the working layer hardness (see Table 1).

The effect of the working layer hardness on the tool performance characteristics studied is also confirmed by the results of the correlation analysis.

In grinding, for example with t = 0.002 mm, the values of the coefficient of pair correlation of Q_w and Q_s with wheel hardness were –0.611 and –0.809, respectively, and exceeded those with the volumetric content V_z (–0.482 and –0.256, respectively). On the contrary, the correlation of the specific cBN consumption and machined surface roughness is more significant for V_z. But on the other hand, the analysis of the constructed regression models suggests that the cBN content and the wheel hardness have opposite effects on the tool performance characteristics studied herein.

It should be mentioned that the tools tested had essentially a random combination of Rockwell hardness values and cBN content. To maintain the experimental integrity, we re-calculated the values of Q_w, Q_s, q, and Ra for the volumetric cBN content in the range from 12.5 to 25%, with the constant wheel hardness of HRC 32, and have found out that the trend of all the previously revealed relations shown in Figs. 1 through 4 remained almost unchanged.

A significant change was noted only in the results of calculations for the wheel with the 100% concentration of cBN, whose hardness was arbitrarily decreased from HRC 44 by about 40%. In that case, it has turned out that wheel wear rate and specific cBN consumption increased by almost 70%, Ra grew by about 30%, while the removal rate decreased by just 1%.

Thus, in view of the above-mentioned adjustment of the experimental results, it has been found out that the wheels with a reduced cBN concentration will provide a noticeably better performance in comparison with wheels having the 100% cBN concentration, provided that they have close harness values.

Experience of diamond roller truing of grinding wheels with a reduced cBN concentration shows that the truing time for an intricate profile is shorter (e.g., by half for the profile dimensions 100 × 20 × 51) in comparison with that for the wheel with the 100% cBN concentration. This reduction of the truing time is achieved owing to the possibility of increasing the depth of cut in truing from 5 to 10 μm.

4. CONCLUSIONS

It has been found out that in internal finish grinding of workpieces of hardened steel KhVG the wheels with a reduced concentration of high-strength cubic boron nitride of grain size V151 (160/125) can offer a better performance in terms of removal rate and specific cBN consumption in comparison to the tools with the 100% cBN concentration.

When grinding with a depth of cut of 0.002 and 0.005 mm the wheels with 12.5 to 18.75 vol % cBN in the working layer provided an 22% higher removal rate and an 2.5-fold smaller specific consumption of the high-strength cBN as compared to the reference wheel with the 100% concentration.

The reference wheel, in turn, has demonstrated better results in terms of wear rate and machined surface roughness. The wear rate of the reference wheel was up to 44% lower and the ground surface roughness *Ra* was 2 to 3 times better in comparison with grinding using the wheels with a reduced cBN concentration.

The application of wheels with a reduced cBN concentration offers one more benefit—the truing time to provide an intricate wheel profile is almost halved.

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