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EFFECT OF THE GLASS-CRYSTALLINE BOND MICROSTRUCTURE ON THE CUTTING ABILITY OF GRINDING WHEELS WITH Al_2O_3 ABRASIVE GRAINS

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Abstract: Standard ceramic abrasive tools are manufactured using glass bonds or mineral resources, in which the microstructure of the bonding bridges cannot be controlled. In this study, a new type of glass-crystalline bond was used to combine mixed abrasive grains from microcrystalline and monocrySTALLINE corundum into an abrasive tool. The glass-crystalline bond has a fine crystalline structure (particle size of the crystalline phase: 1-1.5 μm) and perfectly moistens the abrasive grains. This fact and the generated crystalline phase with a high coefficient of brittle fracture resistance enable the production of tools with a higher porosity and self-sharpening ability in comparison to grinding wheels with the use of industrial bond, which results in high performance indices with a longer service life.

Keywords: alumina grinding wheel, grinding performance, glass-ceramic vitrified bonds

1. INTRODUCTION

Among the important factors influencing the effectiveness of grinding with ceramic tools is the type of abrasive grain, ceramic bond and their microstructure. Properly selected parameters of processing of various materials allow to achieve the so-called effect of self-sharpening of ceramic abrasive tools in the grinding process, which at the same time guarantees high efficiency and surface quality of ground elements.

Although in the world's material processing technologies there is a clear trend towards grinding with tools made of CBN grains, the most important group are still abrasive tools made of conventional

abrasives made of Al_2O_3 . The emergence of new microcrystalline grades of numerous Al_2O_3 abrasive grits in recent years enables the development of new types of tools with different performance characteristics than those of conventional grit tools. Mechanical properties of the grains are very dependent on their microstructure [1-4], which proves that the production of required composite microstructures, especially with mixed grains, is still a challenge. The diversity of grain microstructures requires adjusting the microstructure of ceramic-mixed bonds to them, without which it is impossible to achieve high performance indices while maintaining high porosity of tools. Abrasive grains from Al_2O_3 (also from CBN) are usually bonded with a glass bond, but in the new solutions they are gradually replaced with glass-

crystalline materials or glasses containing various inclusions in the form of fine-dispersion phases or whiskers [5-9]. However, the scale of this effect depends on the volume share, morphology of the amplifying phase and its distribution in the amorphous residue.

The research results presented in this paper are a response to challenges posed to ceramic abrasive tools due to high mechanical strength and high porosity, obtained thanks to the possibility of manipulating the structure and microstructure of new glass-crystalline bonds.

2. METHODOLOGY OF EXPERIMENTAL STUDIES

The object of investigations were abrasive composites made of a mixture of abrasive grains of microcrystalline alumina Cubitron™ by 3M and monocorundum No. 10, as well as glass-crystalline numerous bonds from the glass-forming system $Al_{0.107}B_{0.37}Fe_{0.01}Mg_{0.04}Zn_{0.29}Ca_{0.1}Si^{0.93}O_3$. The glass-crystalline bond was obtained using a typical ceramic technology. The thermal history of the bond was observed in a high-temperature microscope by Leitz Wetzlar.

The ability to crystallize the material was determined by DTA method using a thermal analyzer of MOM Hungary company, adapted to work in air atmosphere from ambient temperature up to 1000°C. A powdered sample of 0.8 g of the material was placed in an aluminium oxide crucible, using aluminium oxide as a reference material. The powdered sample was subjected to heat treatment in the temperature range of 20-1000°C at a constant speed of $\beta=5^\circ\text{C}/\text{min}$ in the full temperature range. Small flat grinding wheels of dimensions 35×10×10 mm with the following characteristics were formed for the operational tests:

- 1×35×10×10-M3X100M5E01-50 – designated as No. 1 industrial grinding wheel,
- 1×35×10×10-M3X100M5VTHE-50 – designated as No. 4 - new bonded grinding wheel,
- 1×35×10×10-M3X100J8VTHE-50 – designated as No. 10 new bonded grinding wheel.

Thermal treatment of the tools was carried out in the PK-4 chamber furnace in an air atmosphere at 940°C and held for 7 hours. The microstructure of thermally treated samples and digested in 10% HF solution was observed using the scanning electron microscope JEOL-JSM-5500 LX Japan.

The aim of experimental investigations was to determine the influence of differences in the structure of small-dimensional flat grinding wheels with dimensions 35×10×10 mm on the period of their durability and the quality of surface treated in the internal cylindrical grinding process.

Before the grinding the workpiece was preliminary ground and the tested grinding wheel was dressed with a single-grained diamond dresser of mass $Q_d = 1.25$ kt. Then the internal diameter of the ground ring was measured (using Links Brand 50-160 sensor diameter of accuracy $\pm 1 \mu\text{m}$) and the external diameter of the grinding wheel (using VIS mmZb 25-50 micrometer of accuracy $\pm 1 \mu\text{m}$). After grinding, the internal diameter of the workpiece and the external diameter of the grinding wheel were again measured in order to determine its volumetric wear V_s . Axial roughness profiles of the machined surface were also measured and on its basis the values of Ra parameter (arithmetic mean deviation of the roughness profile) in μm were determined. The measurements were taken at a measuring position equipped with a Hommel-Tester T8000 contact profilometer manufactured by Hommelwerke GmbH. Table 1 presents the characteristics of the applied grinding process conditions.

Tab. 1. Characteristics of grinding conditions

Process	Reciprocal peripheral internal cylindrical grinding process
Grinding machine	Universal grinding machine RUP 28P by Mechanical Works Tamów SA
Dressing parameters	Dresser: single-grain diamond dressee with mass $Q_d = 1.25$ kt, $n_{sd} = 12\ 000$ rpm, $v_{fd} = 10$ m/s, $a_d = 0.0125$ mm, $i_d = 12$
Grinding parameters	$v_s = 50$ m/s, $v_w = 0.83$ m/s, $q = 60$, $v_{fa} = 20$ mm/s, $a_{e\ tot} = 0.20$ mm, $t_s = 150$ s, $Q_w = 8.29$ mm ³ /s, $Q_{GF} = 4.0$ l/min
Coolant	Grinding fluid (coolant) was prepared as a 5% aqueous oil solution Castrol Syntilo RHS and was administered to the grinding zone by flooding method
Workpiece	Internal surfaces of the bearing rings made of 100Cr6 steel (63 ± 2 HRC), internal diameter: $d_w = 40$ mm, width: $b_w = 18$ mm

After the end of tool life, microscopic observations of the grinding wheel active surfaces under investigation were made with the use of a digital measurement microscope type Dino-Lite Edge AM7915MZT from ANMO Electronics Co.

3. RESULTS AND DISCUSSION

The designed bond is characterized by very good fluidity, which allows to burn tools at low temperature, i.e. 940°C. The change of contours of the binder sample is shown in Fig. 1.

In the thermal processing the bond undergoes the process of crystallization, according to the DTA curve, Fig. 2.

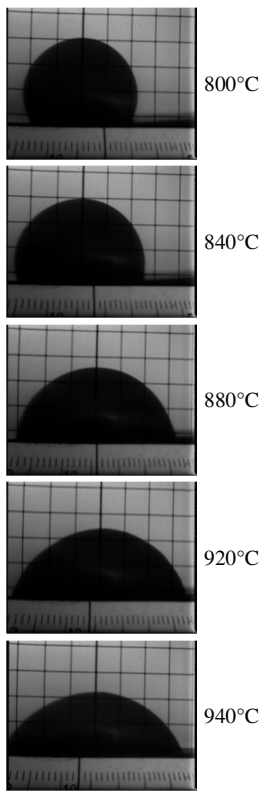


Fig. 1. Results of glass-crystalline bond observation in a high-temperature microscope

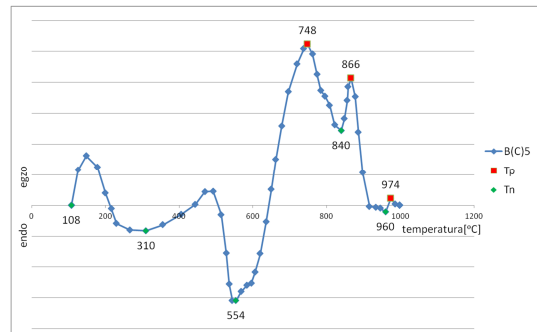


Fig. 2. DTA curve of the bond at $\beta = 5^\circ\text{C}/\text{min}$

The obtained DTA curve is characterized by the occurrence of exothermic areas in the temperature range from approximately 550°C to 960°C . The occurrence of two exothermic peaks indicates a complex mechanism of phase transformations occurring in the material, related to the process of crystallization of individual phases during heat treatment.

SEM analysis confirmed the presence of two different crystalline phases in the binding bridges (Fig. 3), belonging to the following type of structures AB_2O_4 i $\text{AB}_{12}\text{X}_{19}$.

Figure 4 presents a graph of changes in the value of grinding power gain ΔP in the durability period for the grinding wheels under investigation.

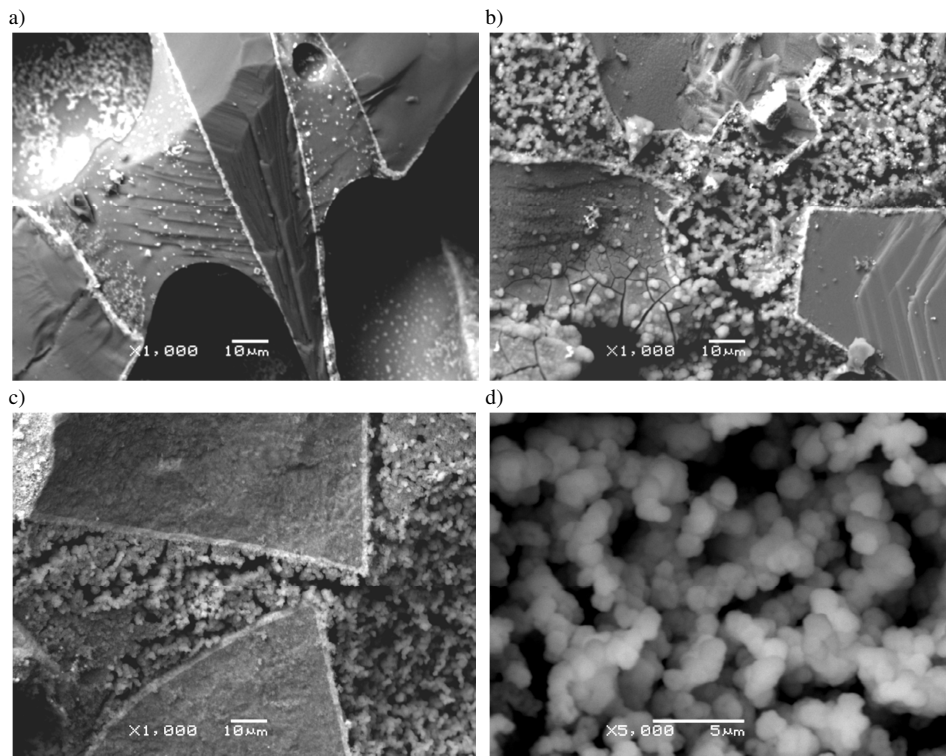


Fig. 3. SEM micrography of abrasive tool breakthroughs facificated at 940°C : a) unsealed bond bridges; b) etched bond bridge in monocorundum wheel; c) etched bond bridge in microcrystalline aluminium oxide wheel; d) bond microstructure

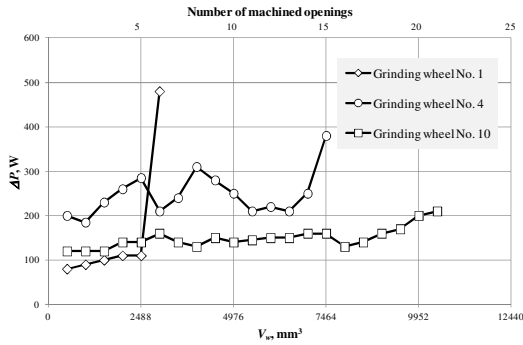


Fig. 4. Diagram of changes in the value of grinding power gain ΔP during the durability period of the tested grinding wheels

Figure 5 presents a graph of changes in the value of the grinding wheel diameter d_s during the durability period for the investigated grinding wheels.

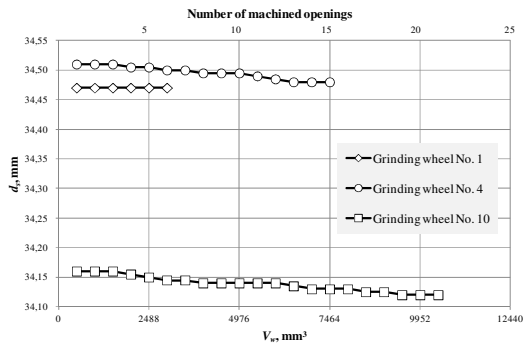


Fig. 5. Diagram of changes in the value of the grinding wheel diameter d_s in the durability period for the tested grinding wheels

Comparison of the obtained results (Figs. 4 and 5) shows that in the process of grinding bearing rings carried out in the same conditions for each of the tested grinding wheels, the cutting capacity of the wheel No. 10 ($V_w = 10450 \text{ mm}^3$) has been maintained for the longest time. The wheel No. 4 ($V_w = 7464 \text{ mm}^3$) worked for about 25% less time. Both tools were characterized by non-standard bond microstructure. Reference wheel No. 1 (used in industry) lost its cutting ability in the adopted grinding process conditions during the sixth ring machining ($V_w = 2986 \text{ mm}^3$), which means that the material removed by it constituted 28.6% and 40.0%, respectively, in relation to grinding wheel No. 10 and No. 4.

Figure 6 presents a graph of changes in the R_a parameter value describing the geometric structure of the surface of machined workpieces and Figure 7 presents its average values determined on the basis of the results of measurements from the whole durability period of the tested grinding wheels.

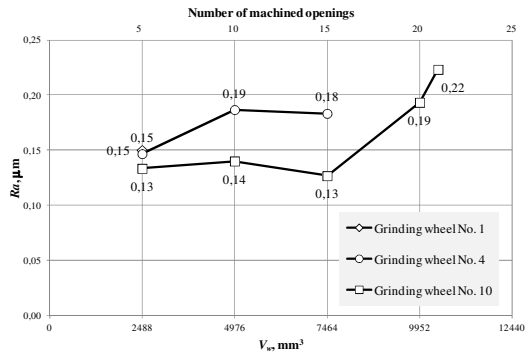


Fig. 6. Values of the R_a parameter describing the geometric structure of the surface of workpieces machined with the grinding wheels under investigation

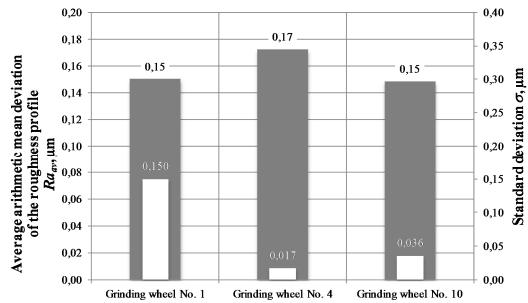


Fig. 7. Average values of R_{aav} parameter describing the geometric structure of machined parts surface determined on the basis of the results of measurements from the whole durability period of the tested grinding wheels

The surface roughness of machined workpieces expressed by R_a parameter was very similar for all evaluated grinding wheels. It ranged from $0.13 \mu\text{m}$ to $0.22 \mu\text{m}$ (Fig. 6), which is the correct value for the described machining process.

In Fig. 8-11 the average values of grinding power gain ΔP_{av} (Fig. 8), grinding wheel volumetric wear V_s (Fig. 9), material removal V_w (Fig. 10) and grinding ratio G (Fig. 11) determined on the basis of the results from the whole durability period of the tested grinding wheels are presented.

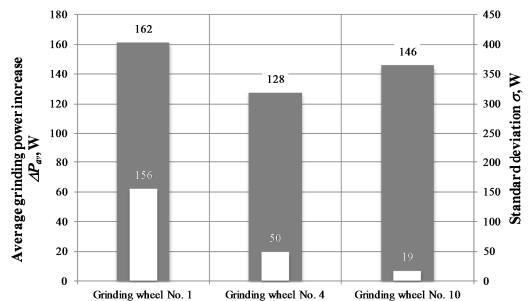


Fig. 8. Average values of the grinding power gain ΔP_{av} calculated on the basis of the results from the whole durability period of the tested grinding wheels

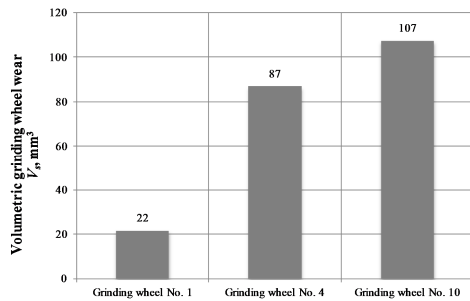


Fig. 9. Average values of volumetric wear of grinding wheel V_s calculated on the basis of results from the whole durability period of the tested grinding wheels

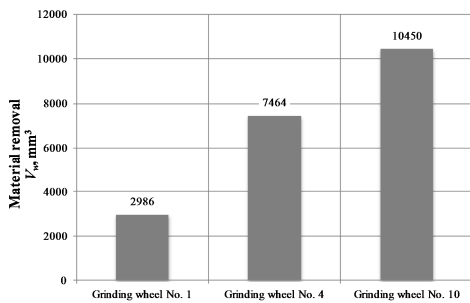


Fig. 10. Average values of material removal V_w calculated on the basis of results from the whole durability period of the tested grinding wheels

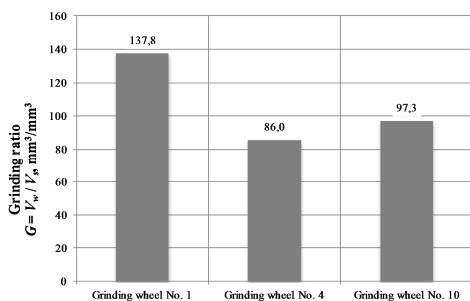


Fig. 11. Values of grinding ratio G calculated on the basis of results from the whole durability period of the tested grinding wheels

In case of all three compared grinding wheels, comparable power consumption values during grinding were measured and their average values are within the range $\Delta P_{av} = 128-162$ W (Fig. 8). It should be noted, however, that in case of grinding wheels No. 4 and No. 10 the average power values were 10% to 30% lower than during the reference operation of grinding wheel No. 1 (Fig. 8).

The biggest difference between the investigated grinding wheels was shown by the measurements of their volumetric wear V_s (Fig. 9). It results from them that in the case of the reference wheel there was no phenomenon of gradual exposure of sharp cutting points of the abrasive grains by the bond, called in the literature as *self-sharpening*. It should be assumed that

it was the ability of grinding wheels No. 4 and No. 10 to self-sharpen that enabled the correct execution of the machining process in a much longer time of their operation and as a result the removal of a much larger volume of processed material (Fig. 10). At the same time it translated into increased (in relation to reference wheel No. 1) volumetric wear shown in Fig. 9.

Grinding ratio G determines the ratio of material removal V_w to the volumetric wear of grinding wheel V_s , which is a very good measure of grinding wheel efficiency and utilization of the cutting potential of the abrasive grains contained in it. Comparison of the G -values presented in Fig. 11 shows about 40% advantage of the reference wheel (wheel No. 1) in comparison with the values determined for wheels with modified microstructure of the bond (wheel No. 4 and No. 10). It results from a slight volumetric wear of grinding wheel No. 1 resulting mainly from dulling of active abrasive grain vertexes. As a result, no new sharp corners of the abrasive grains were exposed and the grinding wheel lost its cutting ability after machining 6 workpieces.

Figure 12 presents microscopic images of active surfaces of grinding wheels recorded during and after grinding using digital measuring microscope type Dino-Lite Edge AM7915MZT from ANMO Electronics Co. The views of grinding wheel surfaces before operation (Fig. 12a, 12c and 12e) prove very high porosity of grinding wheels, which is particularly important in the case of the grinding process of internal cylindrical surfaces, where there is a long zone of contact between the wheel and the workpiece, which significantly hinders the evacuation of chips from the grinding zone and the delivery of coolants.

The analysis of microscopic images recorded after grinding is completed (Fig. 12b, 12d and 12e) shows the highest share of blunted abrasive grains on the active surface of grinding wheel No. 1 (Fig. 12b). Moreover, on the surface of this wheel the intergranular spaces were filled with grinding products, including mainly chips. This phenomenon is very unfavorable from the point of view of stability and repeatability of the grinding process results.

The obtained effect of extending the service life of the designed grinding wheels in comparison to the reference (industrial) grinding wheel is the result of using a new type of glass-crystalline bond. The presence of spherical inclusions ($AB_{11}X_{19}$ – where A: La, Y, Mg; B: Al, X-O) dispersed in the amorphous residue in the bond bridges results in obtaining higher isotropic properties of grinding wheel, while the second crystalline phase (AB_2O_4 , – where A: Zn, Mg, Fe; B: Al) concentrates mainly in the abrasive grain area. This layer, with the spinel structure, has a similar

thermal expansion coefficient to the abrasive grain $7,5 \cdot 10^{-6} \text{ K}^{-1}$ for Al_2O_3 [10] and $8.7\text{-}9.9 \cdot 10^{-6} \text{ K}^{-1}$ for ZnAl_2O_4 [11]. Therefore, unfavourable thermomechanical stresses are minimized in the transition zone between the abrasive grain and the glass-crystalline bond and in the bond ($\alpha_{inclusion} = 8.49 \cdot 10^{-6} \text{ K}^{-1}$) [12]. Moreover, for spherical inclusions the residual thermal stresses are described by hydrostatic stress state ($\sigma_{11} = \sigma_{22} = \sigma_{33}$) [13]. A favourable system of residual thermal stresses in the bond is determined, because the amorphous residue is in the state of compressive stresses in relation to spherical inclusions. This is confirmed by the coefficient of thermal expansion of amorphous phase residues in the bond bridge calculated by the authors (according to Wilkelman and Scott [14]), which amounts to $4.74 \cdot 10^{-6} \text{ K}^{-1}$, which

increases the mechanical strength of tools. The mechanism of grain cracking is mainly based on the course of grain cracking gap (visible surfaces after decohesion in Fig. 2) and not along the grain-bond boundary. The mechanism is also affected by high value of the coefficient of resistance to brittle fracture of spherical inclusions, which for the phase of similar chemical composition may reach the value of $4.6 \text{ MPa} \cdot \text{m}^{1/2}$ [15]. On the other hand, much lower K_{Ic} value for amorphous residue (standard values range from $0.5\text{-}0.6 \text{ MPa} \cdot \text{m}^{1/2}$ [16]) causes that cracks in the shape of meander are formed in it, omitting the spherical phase, which lengthens the path of the fracture. This translates into a strengthening of the tool.

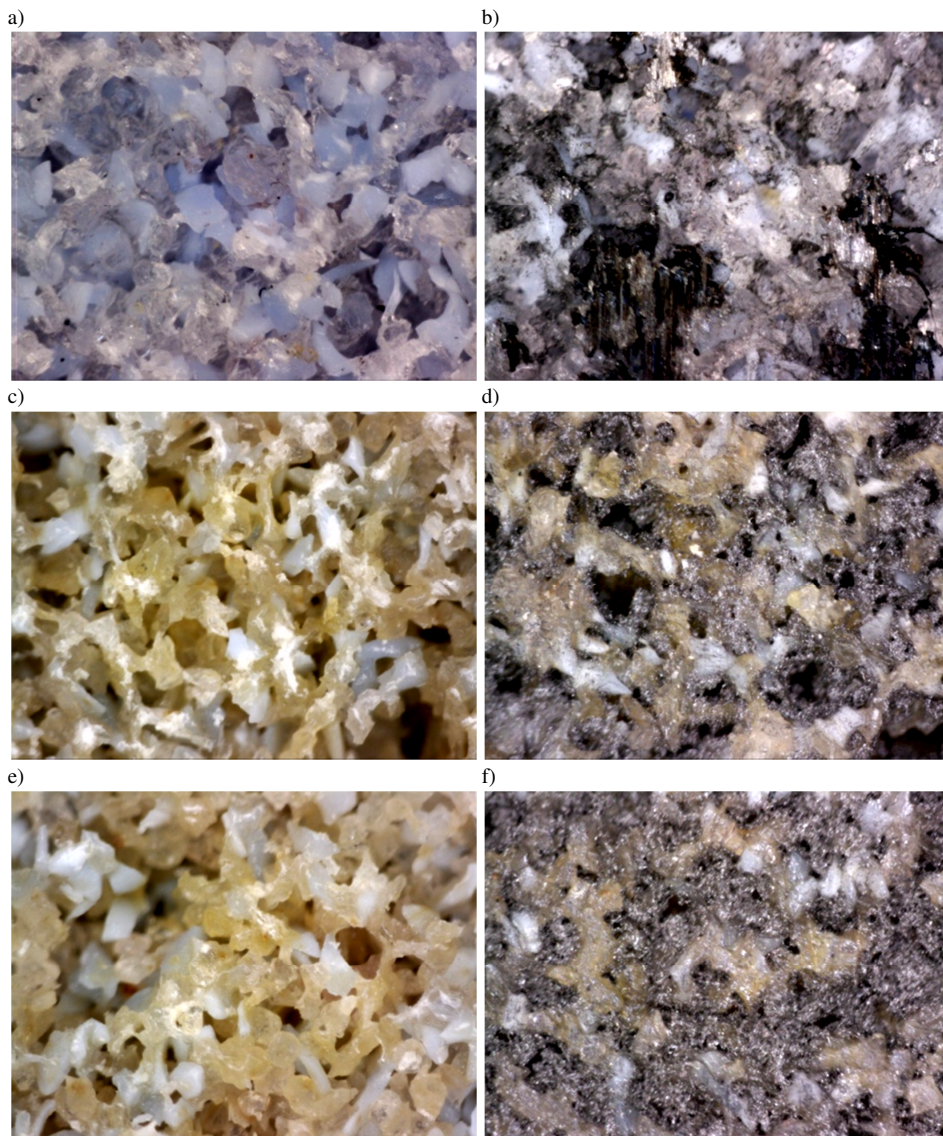


Fig. 12. Microscopic images of active surfaces of tested grinding wheels before (a, c, e) and immediately after the grinding process (b, d, f) – mag. 200 \times : a, b) grinding wheel No. 1; c, d) grinding wheel No. 4; e, f) grinding wheel No. 10

At the same time, due to the microcrystalline structure of the bond, its microwear, which is largely compatible with the wear mechanism of abrasive grains, is possible. This has an impact on increasing the durability of a grinding wheel, especially for an open structure grinding wheel (volume of porous $V_p = 42\%$ and a small share of bond $V_b = 12\%$), which at the same time guarantees high (required) performance indices.

4. CONCLUSIONS

The designed glass-crystalline binder enables the production of tools from microcrystalline alumina and monocorundum with open structure and high self-sharpening ability. The tools can be fired at relatively low temperatures (940°C). Thanks to the microcrystalline structure of the glass-crystalline binder, the micro-cutting process involves systematic (gradual) micro-crushing of grain and binder, which increases the tool life of the grinding wheel. Such a process is defined as self-sharpening and its occurrence in the grinding process is of decisive importance in obtaining repeatable machining results. In the case of designed grinding wheels, self-sharpening is initiated more easily and occurs in a much wider range of operating parameters.

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Nomenclature

Acronyms

CBN – Cubic Boron Nitride
 DTA – Differential Thermal Analysis
 GF – Grinding Fluid
 SEM – Scanning Electron Microscopy

Symbols

a_d – dressing allowance, mm
 $a_{e\ tot}$ – total working engagement (machining allowance), mm
 b_w – workpiece diameter, mm
 d_s – grinding wheel outer diameter, mm
 d_w – workpiece diameter, mm
 G – grinding ratio, mm^3/mm^3
 i_d – number of dressing passes

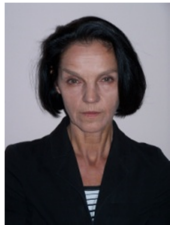
K_{Ic} – fracture toughness, $\text{MPa}\cdot\text{m}^{1/2}$
 n_{sd} – grinding wheel rotational speed while dressing, 1/min
 v_{fa} – axial table feed speed while grinding, mm/s
 v_{fd} – axial table feed speed while dressing, mm/s
 v_s – grinding wheel peripheral speed, m/s
 V_s – volumetric grinding wheel wear, mm^3
 v_w – workpiece peripheral speed, m/s
 V_b – volume of bond in grinding wheel, %
 V_p – volume of pores in grinding wheel, %
 V_w – material removal, mm^3
 P – grinding power, W
 q – speed ratio
 Ra – arithmetic mean deviation of the roughness profile, μm
 Ra_{av} – average arithmetic mean deviation of the roughness profile, μm
 t_s – grinding time, s
 Q_d – diamond dresser mass, kt
 Q_{GF} – grinding fluid flow rate, l/min
 Q_w – material removal rate, mm^3/s
 α – thermal expansion coefficients, K^{-1}
 ΔP – grinding power increase, W
 ΔP_{av} – average grinding power increase, W
 σ – standard deviation

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Biographical notes



Daniela Herman is a research and teaching employee at the Department of Technical Physics and Nanotechnology at the Faculty of Mechanical Engineering of the Koszalin University of Technology. In 1976 she completed her master's degree in Materials Engineering, in 1984 she defended her doctoral dissertation at the Wrocław

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Krzysztof Nadolny received his M.Sc. degree in Mechanics and Machine Design and next Ph.D. (with honors) as well as D.Sc. degree in Machinery Construction and Operation from Koszalin University of Technology, in 2001, 2006 and 2013, respectively. Since 2006 he has been a researcher in the Department of Production

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