Agronomy Research **14**(S1), 1043–1052, 2016

Effect of porosity on the performance of cutting ceramics

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Abstract. The article examines the forecasting performance of the cutting tool equipped with interchangeable plates of carbide oxide ceramics (A_2 – mixed ceramic), by definition porous ceramic tool material affecting its cutting properties. Set correlation of porosity ceramic tools from electrical resistivity removable ceramic plates. Cutting tools having larger electrical resistivity values and, respectively, smaller porosity percentages should be used for machining the most precise components of machine part blanks, since their performance will be better than that of the tools whose ceramic bits have small electrical resistivity values. Based on the established correlation selects ceramic plates for the required machining conditions.

Key words: cutting ceramics, strength, porosity of the material, operation tools, electrical resistivity.

INTRODUCTION

Ceramic cutting tools find ever-widening applications in industrial production; they are used for finishing precision components of machine parts. The number of ceramic materials used for making tools is quite large. This work focuses on carbide oxide ceramics, a material that is used extensively at machine-building enterprises and therefore can be used as a reference point for studying the performance of other ceramic cutting materials.

In spite of the fact that ceramic tools performance depends, first and foremost, on their hardness, apart from other factors, ceramic materials porosity has a sizable effect on it. It is known that the less is the porosity of a tool material, the better are the cutting property and performance of a tool manufactured with the help of powder metallurgy (Margules, 1980; Maksarov et al., 2014). Whereupon this factor virtually does not depend on the method of tool material manufacture – hot pressing, sintering, etc. – a material porosity percentage may be reduced but it is not yet possible to eliminate it altogether. This is equally applicable to all tools made of ceramics, irrespective of its components and structural composition.

Thereby, determining functional relationship between cutting properties of ceramics (e.g., its strength) and its material porosity can be considered as a solution of the problem of forecasting ceramic tools performance.

As a rule, any ceramic material, including carbide oxide cutting tools is solid substance with cavities (pores). The volume of pores, their distribution and dimensions have a sizable effect on a number of properties of ceramic articles and material. E.g., strength of ceramics does not only depend on total porosity but on the sizes of pores and evenness of their distribution throughout the area of the surface under study.

As porosity increases, ceramics strength deteriorates through increased defectiveness of its structure and reduced strength of its bonds. Pores in ceramics have various shapes and outlines, they are unevenly distributed in its volume. Therefore, it is hard to obtain a complete characteristic of porosity. In spite of variety of their shapes, pores can be subdivided into closed ones (impermeable for liquids and gases) and open ones that are in their turn subdivided into dead-end ones (fillable by liquids and gases but not affecting ceramics permeability) and canal-forming ones (open from both ends and creating pore channels).

There are several principal approaches to measuring porosity and analyzing the surface structure of the material under study. The principal methods are the gas absorption one (physical and chemical), mercury injection porosimetry, the gas-dynamic method, etc. Each of those methods proves as the most efficient when measuring material porosity within a strictly defined range (Fig. 1). Therefore, the choice of analysis technique depends very heavily on the presumed structure of material, as well as the types and shapes of the pores.

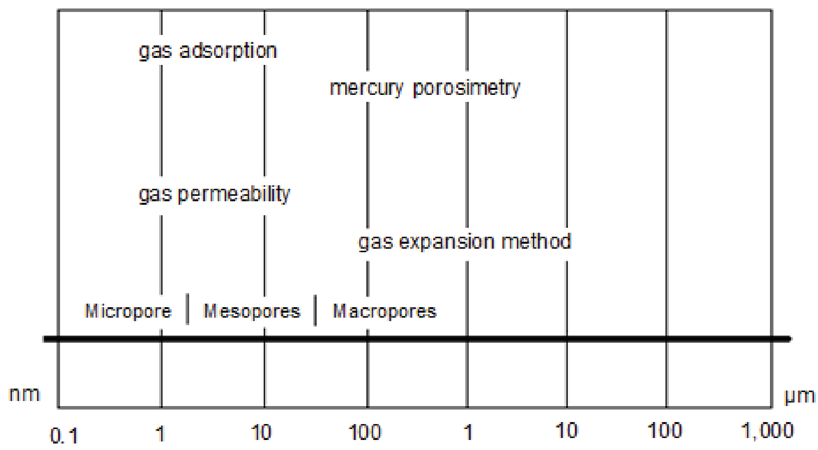


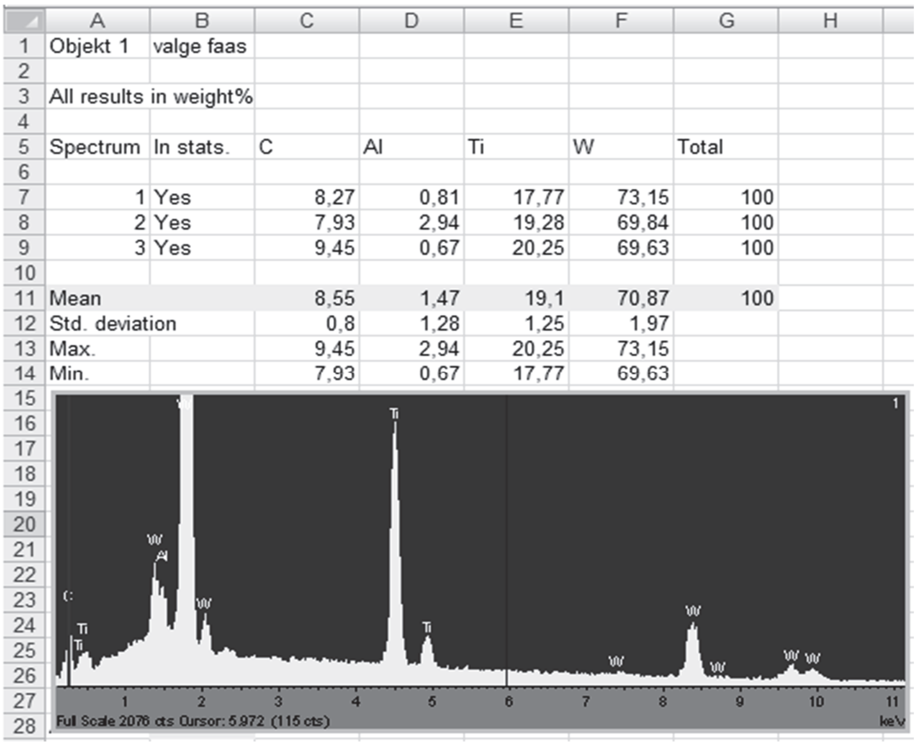
Figure 1. Measuring methods of material porosity depending on the sizes of pores.

Since direct methods of material porosity measurement are extremely complicated and measuring equipment is rather expensive, in ceramics technology this indicator is often assessed by determining other properties directly depending on porosity. We propose to assess material porosity by its correlation dependence on the electrical resistivity of ceramic cutting bits.

MATERIALS AND METHODS

At the beginning of the studies performed in order to determine carbide oxide ceramics strength it was necessary to carry out metallographic surveys that would elicit the structural composition of ceramics, determine the presence of pores and their number.

Metallographic survey data (Fig. 2) permitted us to establish that modern VOK63 type carbide oxide ceramics contain Al_2O_3 – 75% + (Ti, W, Mo)C – 25% (Wittenauer, 1995; Borovskii, 2007).



	A	B	C	D	E	F	G	H
1	Objekt 1	valge faas						
2								
3	All results in weight%							
4								
5	Spectrum	In stats.	C	Al	Ti	W	Total	
6								
7	1	Yes	8,27	0,81	17,77	73,15	100	
8	2	Yes	7,93	2,94	19,28	69,84	100	
9	3	Yes	9,45	0,67	20,25	69,63	100	
10								
11	Mean		8,55	1,47	19,1	70,87	100	
12	Std. deviation		0,8	1,28	1,25	1,97		
13	Max.		9,45	2,94	20,25	73,15		
14	Min.		7,93	0,67	17,77	69,63		

Figure 2. Percentage ratio between carbide oxide ceramics phases.

The structure of cutting ceramics was studied with the help of a scanning electron microscope in order to confirm the extent of porosity. The photos of the front surface of a ceramic cutting tool are presented in Fig. 3. As it can be seen in this picture, the sample under study has pores of different sizes and structures. It is known that more porous ceramics has a coarser grain size (about 3–4 μm) as compared to ordinary ceramic (having no pores) (about 1–2 μm). The data of the sample of ceramic under study coincide with a number of literature ceramic data (Dunand & Grabowski, 2000; Maksarov et al., 2014).

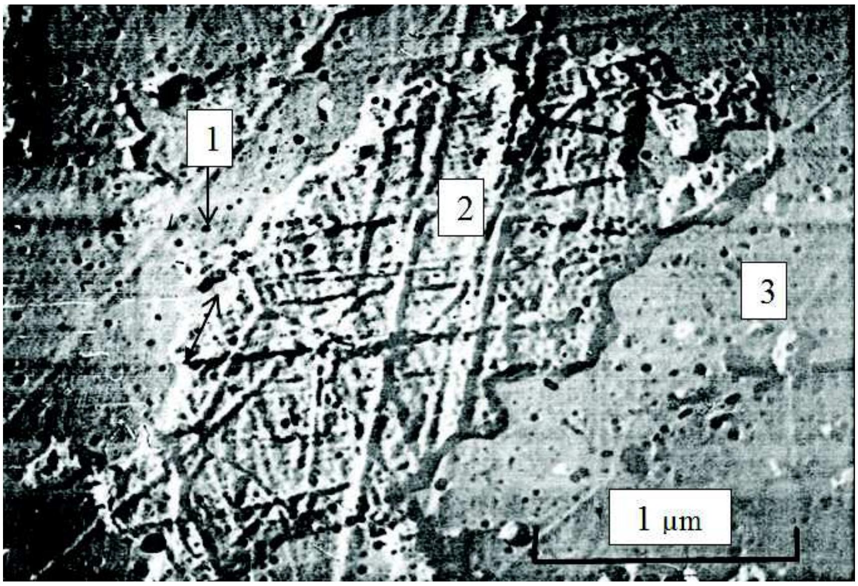


Figure 3. Carbide oxide ceramics pores: 1 – pores, 2 – (Ti, W, Mo)C, 3 – Al_2O_3.

It is difficult to use on the shop floor the methods ordinarily used for determining the number of pores whose size amounts to 0.1–10 nm Ceramics porosity can only be assessed with the help of electronic microscope and the ceramic bit must be thoroughly prepared for survey in a special way; it is a time-consuming process.

We propose to solve the above problem using correlation dependence between cutting ceramics porosity and its strength determined as a function of the ceramic bit material electrical resistivity.

RESULTS AND THEIR DISCUSSION

Several samples of replaceable multifaceted cutting bits made of the same grade cutting ceramics (VOK63) were selected for determining strength of ceramic cutting bits having a certain porosity percentage. Each of them had a different electrical resistivity value. The samples of ceramic bits were divided into two groups. The samples having electrical resistivity parameters $R \approx 10\ \Omega$ were included into the first group, the samples having electrical resistivity parameters $R \approx 100\ \Omega$ were included into the second group.

Electrical resistivity parameters were determined with high precision with the help of a mercury contact gauge (Margules, 1980; Maksarov et al., 2014).

The ceramic bits chosen for further tests were specially prepared. The front surfaces of ceramic cutting bits were thoroughly polished in order to determine the state of microstructure parameters.

Each sample of ceramic bits was subjected to an effect simulating the processes that accompany metal cutting.

The samples of ceramic bits were subjected to mechanical loads equal to $P = 3 \cdot 10^4$ N, simulating the state of a cutting bit subjected to compression deformation.

After load exposure, the ceramic cutting bit samples were exposed to thermal action equal to $T = 600$ °C, simulating heating of ceramic cutting tools during machining of workpieces. The ceramic samples were heated in thermal jacket. A chromel-copel thermocouple installed on its border contract permitted to assess the thermal effect on the material of the cutting bit under study precisely enough.

We propose to assess strength of ceramic bits through its relationship with porosity using a formula proposed by M.Yu. Balshin (Balshin, 1972):

$$\sigma = \sigma_c \left(1 - \phi\right)^{\lambda} , \qquad (1)$$

where: σ_c is the strength of non-porous or semi-porous body, for VOK63 carbide oxide cutting ceramic the value of $\sigma_c = 322$ MPa, T is the exponent, for the conditions under study $\lambda = 3$, ϕ is porosity, %. The results of ceramic tool cutting process simulation can be seen in Table 1.

Table 1. The results of ceramic tool cutting process simulation

The initial state of the sample			The condition of the sample under load				The condition of the sample under the influence of temperature			
R, Ω	ϕ, %	σ, MPa	R, Ω	P, N	ϕ, %	σ, MPa	R, Ω	T, °C	ϕ, %	σ, MPa
10	12	218	12	$3 \cdot 10^4$	16	190	11	600	14	202
100	8	240	103	$3 \cdot 10^4$	11	236	102	600	10	238

The obtained results permitted us to create characteristic curves linking electrical resistivity parameters of ceramic cutting bits to porosity (ϕ) and strength (σ) of the ceramic material. The electrical resistivity-vs-porosity and strength curves for carbide oxide cutting ceramic whose electrical resistivity values are approximately 100 Ω in the initial state $R_0 = f(\phi, \sigma)$, after exposure to load $R_P = f(\phi, \sigma)$ and after thermal exposure $R_T = f(\phi, \sigma)$ are shown in Figs 4 and 5.

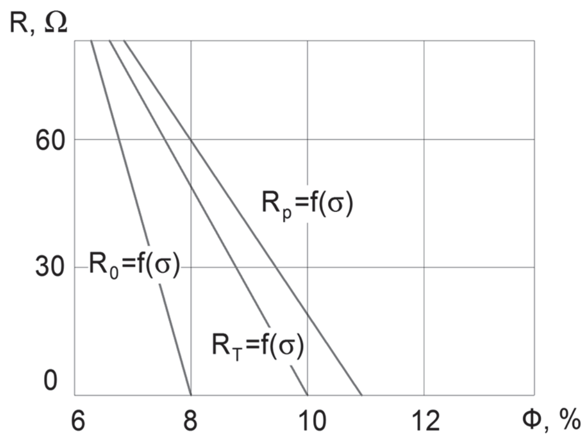


Figure 4. Ceramics electrical resistivity vs. porosity curves in the initial state $R_0 = f(\phi)$, after exposure to load $R_P = f(\phi)$ and after thermal exposure $R_T = f(\phi)$.

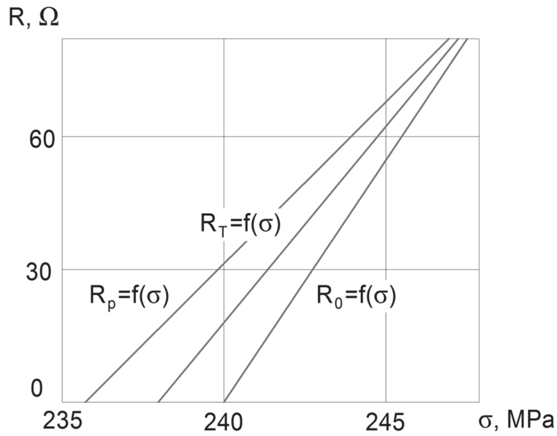


Figure 5. Ceramics electrical resistivity vs. strength curves in the initial state $R_0 = f(\sigma)$ after exposure to load $R_P = f(\sigma)$ and after thermal exposure $R_T = f(\sigma)$.

We have constructed a $R = f(\phi, \sigma, K)$ functional relationship where K is a coefficient replacing load and temperature values during cutting process simulation in order to determine generalized relationship between electrical resistivity of ceramic material and the porosity and strength values of ceramic cutting bits.

In the process of experimental studies, we have obtained $R = f(\phi)$ and $R = f(\sigma)$ characteristic curves that permitted us the shape a 3D area and to demonstrate the existence of a relationship between electrical resistivity of a ceramic material, its strength and porosity percentage (Fig. 6).

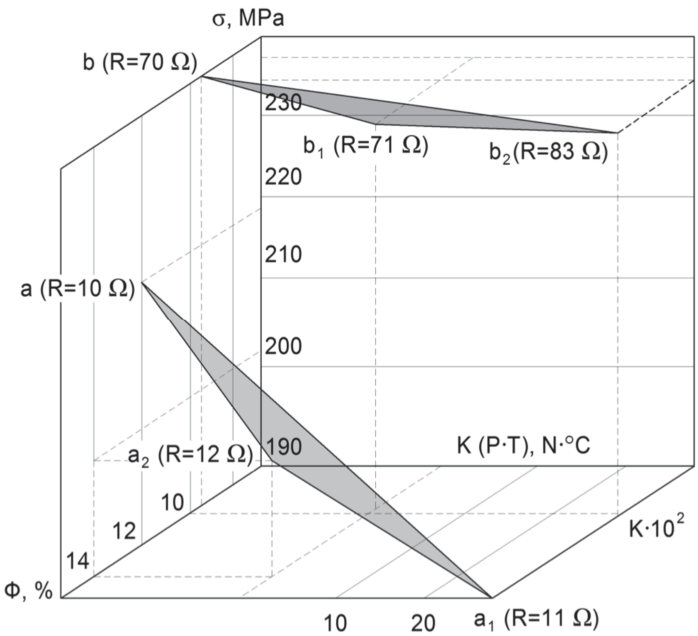


Figure 6. 3D curve $R = f(\phi, \sigma, K)$ constructed on the basis of experimental data.

Force actions created in the process of cutting bring about an increase in electrical resistivity of ceramic material and its porosity percentage.

Changes accompanying the cutting process (thermal heating) also slightly increase the electrical resistivity of ceramic material and its porosity percentage, but to a lesser extent than under load.

All samples of ceramic cutting bits underwent similar strength and porosity changes, irrespective of the value of their electrical resistivity. However, under identical external impacts the samples of ceramic bits whose electrical resistivity values were approximately equal to 10 Ω demonstrated greater quantitative differences.

The ceramic bits whose electrical resistivity values were approximately equal to 100 Ω have relatively small porosity percentage, and under temperature and force impacts accompanying the cutting process their strength is higher than that of ceramic bits with relatively small electrical resistivity values approximately equal to 10 Ω.

A detailed survey of ceramic cutting bit samples' microstructure was carried out in order to determine strength parameters of the same grade ceramics having different electrical resistivity values.

The ceramic samples were specially prepared according to the procedure described in works (Vaidyanathan et al., 1999; Matryona, 2004).

After that, the average diameter of carbide grains was determined with the help of computer software determining the parameters of structural components of the ceramic material under study chosen in the microscope field of view. The cross dimension of a grain L taken at certain increments (0–1 μm, 1–2 μm, 2–3 μm) chosen accepted as the parameter value. In its turn, the number of grains of each size within a preset range can be used as a basis for obtaining relative frequency values, i.e. the numbers of occurrences of each variant of the chosen parameter.

Relative frequency was determined by the formula:

$$F = \frac{A}{200}, \% \tag{2}$$

where: A is absolute frequency, i.e. the number of carbine grains of a given size in a certain range; 200 is the total number of grains under survey within the chosen range.

Mathematical statistics method permitted us to obtain precise measurements whose results were used to determine other values.

The average diameter of a carbide grain was determined by the formula:

$$D_{av.} = \frac{\sum m \cdot x}{\sum m}, \ \mu\text{m}, \tag{3}$$

where x is the diameter of carbide grains in each group, m is the frequency of a group occurrence.

The absolute value of a carbide grain diameter $D_{av.abs.}$ was determined by multiplying the obtained value of average diameter of carbide grains $D_{av.}$ by the microscope eyepiece division value used by the software *E*:

$$D_{av.abs.} = D_{av.} \cdot E, \quad (4)$$

Strength characteristics depending on grain size *σ* = *f*(*L*) were determined by formula (Zhukov, 2011):

$$\sigma = 0{,}37L^{-\frac{1}{2}}, \text{ MPa}, \quad (5)$$

where *L* is the average grain size, μm.

The data permitting to construct characteristic curves for ceramics having different electrical resistivity values (porosity changes vs. strength characteristics and even grain size changes vs. relative occurrence frequency and strength value) were obtained by formula (1) (Fig. 7).

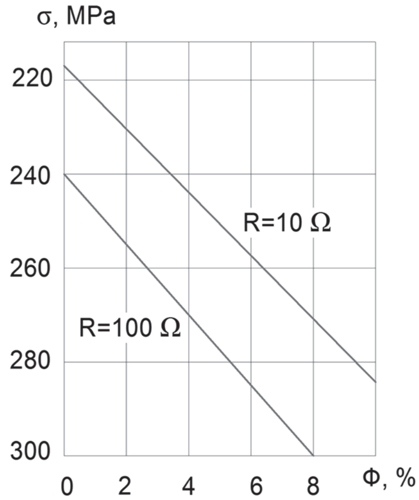


Figure 7. Porosity change vs. strength characteristics and even carbide grain size changes vs. occurrence frequency and strength value curves.

Determined strength values of ceramic material with different electrical resistivity parameters depending on carbide grain sizes demonstrated that all the cutting ceramic bit samples under study demonstrated nearly the same carbide grain occurrence frequency density. However, at the same time grain size fluctuation ranges were different. Ceramic bits with electrical resistivity $R \approx 10\ \Omega$ had a wider grain size fluctuation range.

The root-mean-square values of strength parameters of the ceramic bits under survey are tabulated in Table 2.

Table 2. The RMS values of the strength characteristics of ceramics

R, Ω	D_{CP}, μm	$\sigma = 0.37L^{-\frac{1}{2}}$, MPa	ϕ,%	$\sigma = \sigma_c (1 - \phi)^T$, MPa
10	2,2	171	12	218
100	1,5	232	8	240

The resulting relationships confirm again that ceramics strength characteristics improve as porosity decreases, whereupon ceramics whose electrical resistivity $R \approx 100$ Ω was significantly stronger than that with electrical resistivity $R \approx 10$ Ω because it had a finer structure and a smaller porosity percentage.

Structural parameters of ceramic plates have a great influence on the working ability of cutting tool equipped with them and on the processing quality. The smaller the carbide grain size, larger the cumulative line of carbide grain boundary extension, lower the percentage of material porosity, and more the quantity of carbide grain in the definite bulk of material, the higher the wear-resistance of the cutting tool (Maksarov et al., 2014). Influence of the value of electrical resistance on the wear of clearance face of ceramic plate (h_3) and thus on the working ability of tool is also specified by the structural parameters of the sample. The more the value of the electrical resistance of ceramic plate is, the better microstructural parameters are. According to them, the tool performance time under the constant processing modes (t, S, v) rises considerably, that is the tool life period (T) increases or cutting distance, which allows us to correct essentially the processing speed increasingly and thus to increase the working ability of tool on the preservation of standard wear value (q.v. Table 3).

Table 3. Cutting distance with wear h_3 = 0.5 mm of rear surface

Φ, %	R, Ом	Cutting distance with wear h_3 = 0.5 mm of rear surface, m		
		V = 1,64 m s^{-1}	V = 2.35 m s^{-1}	V = 3.14 m s^{-1}
12	10	26,282	25,641	20,512
8	100	41,000	40,000	32,000

Comparison test showed that the wear-resistance of ceramics of grade VOK63 with R = 100 Ω is 1.56 times high in comparison with VOK63 ceramics with R = 10 Ω on steel cutting under the same parameters of cutting modes v, S, t.

CONCLUSIONS

The estimation of influence of porosity is conducted on specific electric resistance of ceramic material at the simulation of cutting process.

It was found that in the initial state a structure and porosity of cutting ceramics can be estimated on the size of specific electric resistance.

Dependence was set between durability and specific conductivity of ceramic material.

Comparison test showed that the wear-resistance of ceramics of grade VOK63 with electrical resistivity $R = 100\ \Omega$ is 1.56 times high in comparison with VOK63 ceramics with $R = 10\ \Omega$ on steel cutting under the same parameters of cutting modes.

Thereby, we can conclude that the greater is the electrical resistivity value of a ceramic cutting tool, the better that tool will perform.

Cutting tools having larger electrical resistivity values and, respectively, smaller porosity percentages should be used for machining the most precise components of machine part blanks, since their performance will be better than that of the tools whose ceramic bits have small electrical resistivity values.

Simulation of cutting process by application to the cutting of ceramics of different load and temperature also demonstrated the existence of a relationship the preservation of the specific conductivity with porosity and strength of ceramics.

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