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Edvin GEVORKYAN
Mykola PROKOPIV
Mirosław RUCKI
Dmitrij MOROZOW

DURABILITY AND EXPLOITATION PERFORMANCE OF CUTTING TOOLS MADE OUT OF CHROMIUM OXIDE NANOCOMPOSITE MATERIALS

TRWAŁOŚĆ I WŁAŚCIWOŚCI EKSPLOATACYJNE NARZĘDZI SKRAWAJĄCYCH WYKONANYCH Z NANOKOMPOZYTU TLENKU CHROMU

This article is devoted to nanoscale composite materials based on Cr_2O_3 obtained by the activated electric fields sintering procedure. In the paper, exploitative properties of the sintered system of Cr_2O_3 – AlN nanocomposite was examined. Mechanical properties of the material were examined, especially from the perspective of its performance in the cutting tools. In particular, its wear was tested at different cutting speeds, as well as for intermittent hard cutting, and the results were compared with other materials available in the market. Compared to other cutting tools of the same class, Bichromit-R performed the same lifetime for 3-5 times higher cutting speeds, or up to 45% longer lifetime for the same cutting speed. The results lead to the conclusion that composite nanostructure improves substantially exploitation characteristics of the cutting tools.

Keywords: *exploitation, durability, nanocomposite, cutting tool.*

Artykuł jest poświęcony właściwościom eksploatacyjnym materiałów kompozytowych na bazie Cr_2O_3 wytworzonych metodą spiekania w polu elektrycznym. W szczególności poświęcono uwagę nanokompozytowemu spiekowi Cr_2O_3 – AlN wykorzystywanemu do wytwarzania narzędzi skrawających. Zbadano właściwości mechaniczne materiału z uwzględnieniem trwałości ostrzy i powierzchni skrawających. Zbadano zużycie przy różnych prędkościach skrawania w warunkach ciągłych i przerywanych. W porównaniu do ostrzy podobnej klasy, np. Bichromit-R, badane płytki wykazywały podobną trwałość przy wyższych 3 do 5 razy prędkościach skrawania, albo pracowały ok. 45% dłużej przy tych samych prędkościach. Wyniki badań prowadzą do wniosku, że nanostruktura materiału kompozytowego znacząco polepsza właściwości eksploatacyjne ostrzy skrawających.

Słowa kluczowe: *eksploatacja, trwałość, nanokompozyty, narzędzia skrawające.*

1. Introduction

In the engineering systems, even though the lifetime is prolonged, the maintenance cost increases accordingly when fault incurs [7]. In order to reduce expenses, computer-aided maintenance and reliability systems are often applied, as it was reported in case of conveyor belts [19], as well as computer simulation methods [13]. In the context of Industry 4.0, Big Data gains increasing importance [8].

Durability of cutting tools, especially during machining of hard materials, is a subject of many research works [16]. When selecting proper cutting tool for the particular machining task, optimal durability is one of the requirements [1]. One of research directions to prolong cutting tools lifetime is the formation of cutting edge microgeometry which is designed by special processes after grinding or after deposition of the thin layer [28]. There are reports on various layers of nanoscale thickness, e.g. nanocrystalline Al_2O_3 layer deposited by MOCVD on cemented carbide cutting tools [24]. In fact, 85% of all cemented carbide tools are coated [3], but also ceramic materials are coated in order to improve their performance and durability. For instance, Liu et al. proposed novel quaternary coating on the surface of silicon nitride ceramic cutting tool and investigated its dominant wear mechanism [18]. In another reported study, Al_2O_3 was coated on the surface with CaF_2 nanolayer by non-uniform nucleation method, so the mechanical properties of ceramic tools coated with nano-solid lubricant have been significantly improved [4]. It was demonstrated also, that PVD coatings and ALD + PVD hybrid coatings deposited on sialon tool ceramics performed better exploitative properties in comparison with a coating (Ti,Al)N obtained by the conventional method [26].

However, any additional operation of coating, especially with nanolayers, generates increasing costs. Thus, another way to improve durability and performance of ceramic cutting tools is directed to its microstructure formation. It was reported that doping with a small amount of Eu_2O_3 decreases the bulk density and wear resistance of high-alumina ceramics [17]. Since ceramic-matrix composites are outstanding in their ability to withstand high temperatures, in addition their hardness and wear resistance, carbon fiber ceramic-matrix composites are applied, as well as ceramics armed with carbides, nitrides, oxides, and their combinations, including composites with carbon nanotubes and carbon nanofibers [5].

This paper is devoted to the nanocomposite Cr_2O_3 materials produced by the activated electric field sintering procedure. As it will be demonstrated below, its fabrication is cheaper and exploitative properties are better than that of other ceramic cutting tools available in the market.

2. Materials and methods

There are various methods for effective nanopowder consolidation available, and they make possible to obtain materials with a nanosize structure. These methods, such as a hot isostatic pressing (HIP), the high-frequency induction heat sintering (HFIHS), rapid omnidirectional compaction (ROC), pulse plasma sintering (PPS), the ultra high pressure rapid hot consolidation (UPRC) are quite fully described in works [9, 14, 20, 25].

Each of these methods has some advantages and disadvantages in case of sintering mono and polydispersed electrical conductive and non-conductive nanopowders. Thus, widely applied SPS (Spark Plasma Sintering) method enables to get nanostructured bulk materials from refractory compounds, such as Al_2O_3, SiC, B_4C, $MoSi_2$ etc. [2]. In this method, pulses of current are applied during hot-pressing. In the researches, modified patented field activated sintering method was used with alternating current of 1500-2000 A at voltage 5-10 V [10].

At present, Al_2O_3 is perhaps most widely used material for cutting tools [27]. The chromium oxide (Cr_2O_3) has a crystalline structure similar to Al_2O_3, but it performs slightly higher microhardness 29 GPa compared to Al_2O_3 (28 GPa) because of the strong cohesion.

Chromium oxide nanopowder is obtainable with various methods [22], but there are difficulties in its sintering. In the experiments, the high-density Cr_2O_3 for cutting tools inserts was sintered using typical powders with some additives AlN [15]. This way physico-mechanical properties of materials were considerably improved because of grains nanosize kept by the abovementioned hot-pressing with the electric field [10, 21]. The patented method [12], with reduction of temperature and time of sintering, activates the compression and consolidation mechanisms during sintering process, and also enables to perform compaction of materials otherwise difficult for sintering. As it was demonstrated, short sintering time prevented the growth of grains and ensured improved mechanical properties of the bulk material [11].

Moreover, variation of sintering parameters provides different phase structure of the same material. For example, when the same proportion Cr_2O_3 – 10 wt% AlN was sintered at different temperatures, obtained phase composition of bulk material differed substantially: the sample sintered at T=1500 °C consisted of two phases only, white and grey (marked T1 and T2 in Figure 1), while the one sintered at T=1700 °C had additional dark phase (marked T3 in Figure 1). Table 1 presents the results of quantitative analysis of the obtained phase structures.

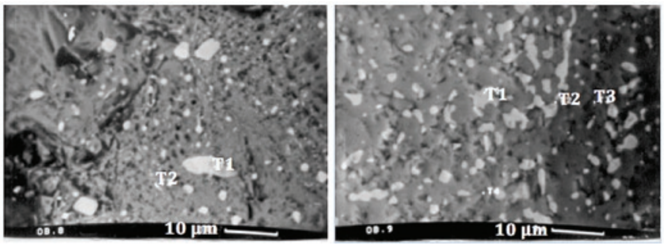

Fig. 1. Photomicrograph of Cr_2O_3 – 10 wt% AlN sintered at T=1500 °C with two phases T1 and T2 (left) and sintered at T=1700 °C with additional phase T3 (right)

Quantitative analysis showed that the dark phase contained large amounts of aluminum, almost two times more that the grey phase. It was found that the dark phase consisted of hard solution $Cr_{1.4}Al_{0.6}O_3$, while the dominant substance in the grey phase was chromium oxide Cr_2O_3.

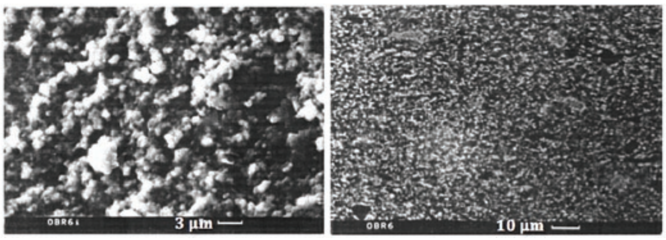

Fig. 2. Fractogram of ceramic fracture Bichromit-R (left) and structure of the surface layer of Bichromit-R after diamond processing (right)

This methodology enabled to obtain the patented material Bichromit-R with nanodispersed structure seen both after fracture test and after diamond grinding, as shown in Figure 2.

Durability tests were carried out during cutting the details made out of steel ШХ-15 (Russian nomenclature), which corresponded with 100Cr6 (ISO standard) and with 52100 (ASTM, USA standard). Hardness of the samples was HRC 58-62. Other steel was used for the evaluation of overall cutting performance of different tool materials. It was steel 30ХГСА (Russian nomenclature), which corresponded with 55 Cr13 (ISO standard) and with 5147 H (ASTM, USA standard) of hardness HRC 58. The machined samples belonged to the group of materials ISO H which contains hardened and tempered steels with hardnesses >45 – 68 HRC. Common steels include carburizing steel (~60 HRC), ball bearing steel (~60 HRC) and tool steel (~68 HRC). Hard types of cast irons include white cast iron (~50 HRC) and ADI/Kymenite (~40 HRC). Constructional steel (40–45 HRC), Mn steel and different types of hardcoatings, i.e. stellite, P/M steel and cemented carbide also belong to this group. Typically, hardness of part machined by turning fall within the range of 55–68 HRC.

No cooling or lubricating was applied. Geometrical features of the sintered inserts and machined samples, as well as the cutting conditions are summarized in the Table 2.

3. Results and discussion

3.1. Mechanical properties

The mechanical properties of the material obtained on the base of Cr_2O_3, called Bichromit-R, were compared with other available ceramic instrumental materials. Since ceramic is a brittle material, increased viscosity is advantageous for its further performance. Figure 3 presents a diagram of stress intensity factors K_{Ic} obtained for different materials typically used for cutting tools inserts manufacturing. Material Bichromit-R performed K_{Ic} above 9 MPa $m^{3/2}$ which indicated higher crack-resistance and hence longer durability than Comp-10, DBC or HC2 materials.

In the Table 3, there are data on main physical characteristics of some cutting tool ceramic materials, compared to Bichromit-R. It is noteworthy that with similar hardness and grain size, Bichromit-R performs better properties than other materials. Above all, its fracture toughness is almost twice higher than for other materials, which indicates high ability of Bichromit-R to resist fractures during cutting

Table 1. Distribution of Cr, Al, O in samples of Cr_2O_3 – 10 wt% AlN sintered at different temperatures

Sintering parameters P=30 MPa	Content of elements, wt%								
	White phase, T1			Grey phase, T2			Dark phase, T3		
	Cr	Al	O	Cr	Al	O	Cr	Al	O
T=1500°C	98.529	0.101	0.292	89.311	6.286	3.906	-	-	-
T=1700°C	96.479	1.729	1.026	81.082	13.172	5.698	71.464	23.735	4.804

Table 2. Geometrical features and cutting conditions in experiments

Geometry of the insert	Intermittent cutting	High-speed cutting	Cutting performance test
Dimensions: 12.5×12.5×4.75 mm $l_f = 0.2$; $r = 0.8$ Working angles: $\gamma_0 = -6°$; $\alpha_0 = 6°$; $\varphi = 75°$; $\varphi_1 = 15°$; $\lambda_c = 0°$.	$f = 0.05$ mm/rev; $a = 0.1$ mm; Cutting speeds from $v_c = 60$ to 120 m/min	$f = 0.075$ mm/rev; Cutting speeds from $v_c = 25$ to 500 m/min	$f = 0.5$ mm/rev; $v_c = 104$ m/min

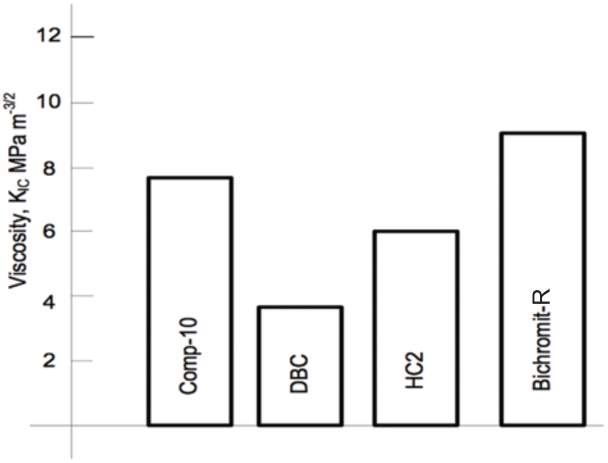

Fig. 3. Fracture toughness diagrams of several cutting tool materials

Table 3. Mechanical characteristics of the Cr_2O_3-based Bichromit-R compared with some ceramic materials

Ceramic type	CC-650 Sweden Al_2O_3	BOK Russia Al_2O_3	Silinite-P Ukraine Si_3N_4	Bichromit-R Ukraine Cr_2O_3
Hardness, HRA	93	92-93	92-94	92-94
Density, g/cm^3	3.97	4.52	3.2-3.4	5.6
Compression strength, MPa	-	-	2500	2600-2800
Bending strength, MPa	480	650	500-700	600-800
Fracture toughness, MPa m$^{1/2}$	6.1	5.6-6.0	4.5	8-10
Grain size, μm	4	2-3	2-3	2-3

operations. This qualifies it for such applications as high speed cutting of hard-tempered cast irons, steel and alloys.

3.2. Durability

The durability comparative tests were performed for intermittent cutting. This type of work conditions is characterized by impact stresses during tool entry, cyclical temperature fluctuation at contact zones between tool and detail, and severe mechanical loading of cutting edge, which usually lead to premature tool failure by fracture [23]. Damage mechanics in intermittent hard cutting can be considered as a combination of microscopic damage and macroscopic fracture of the tool material [6].

The cutting tool made out of Bichromit-R was compared with the one from HC-2 series, based on the aluminum oxide with additions of titanium carbide (Al_2O_3-TiC), produced by NTK. This material is designed and recommended for cutting of hardened steels up to HRC65. In the tests, the steel 5XHM (Russian nomenclature) of HRC 60-63, corresponding with 56CrNiMoV7 (ISO) was machined. In Fig. 4, there are graphs obtained during intermittent cutting at feed $f = 0.05$ mm/rev; $a = 0.1$ mm.

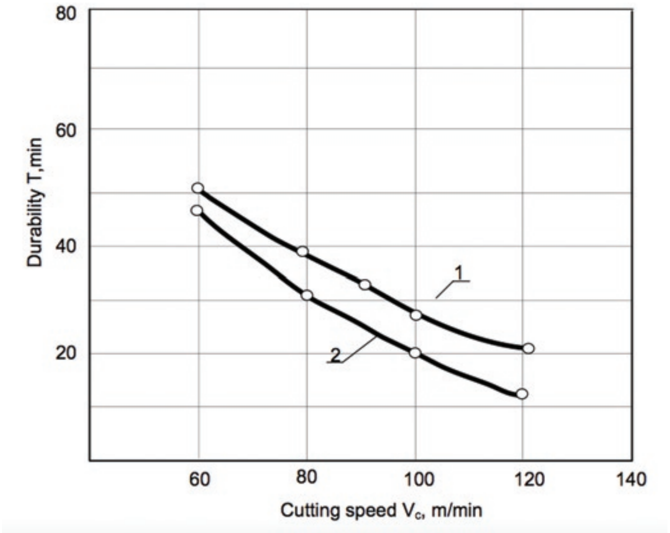

Fig. 4. Durability versus cutting speed during intermittent cutting at feed $f = 0.05$ mm/rev; $a = 0.1$ mm; 1 – Bichromit-R, 2 – HC-2

It should be noted that the lifetime of Bichromit-R cutting tools was considerably better than that of HC-2 especially at higher cutting speed. Namely, while at $v_c = 60$ m/min difference was insufficient, ca. 6%, at doubled speed of 120 m/min Bichromit-R lifetime was ca. 40% longer.

3.3. High-speed cutting

In order to assess the cutting speed influence on the wear of Bichromit-R cutting tools, some tests were carried out. Figure 5 presents the example of results obtained for three different tool materials, namely Bichromit-R, Silinite-P, and BOK-71 (Russian nomenclature). The measure of the wear is the overall path length L [m] of the cut material during machining, before the destruction of the blade. Significantly, the path length ca. $L = 20{,}000$ m may be obtained with Silinite-P at cutting speed $v_c = 50$ m/min, with BOK-71 at $v_c = 100$ m/min, while with Bichromit-R at $v_c = 300$ m/min. Moreover, the path length ca. $L = 15{,}000$ m may be obtained with Silinite-P at cutting speed $v_c = 70$ m/min, with BOK-71 at $v_c = 130$ m/min, while with Bichromit-R even at $v_c = 500$ m/min. In terms of durability it can be stated that compared with Silinite-P and BOK-71, similar cutting work can be done with Bichromit-R tools, but at the cutting speeds 3-5 times higher.

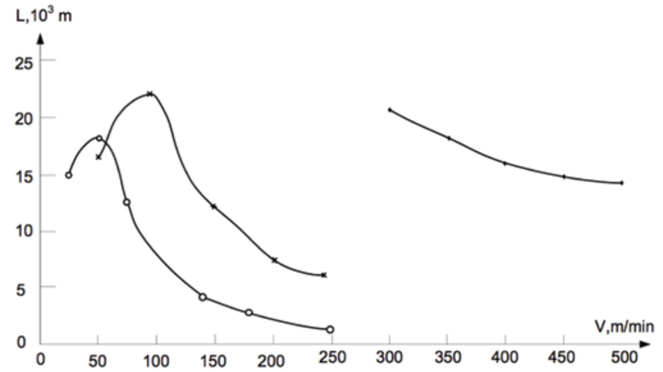

Fig. 5. Cutting speed influence on the wear of a cutting tool h_3 *= 0.4mm, during turning of steel ШХ-15 (HRC 58-62) at f = 0.075 mm/rev, and p = 0.2 mm, -o- Silinite-P; -✕- BOK-71; -□- Bichromit-R*

3.4. Cutting performance

It should be noted that some operational cutting tests were conducted in-situ by the Volkswagen company (Germany), and they showed that machining with cutting tools made out of Cr_2O_3 material provided high quality of the treated surface of details. That quality was close to the one obtainable by polishing. Other industrial tests were performed at the State Enterprise “Malyshev Plant” (Kharkiv, Ukraine) and they demonstrated that in some turning operations Bichromit-R performed better than other materials available in the Ukrainian market, e.g. “Tomal” cubic boron nitride tools. Thus, ceramics on the basis of chromium oxide could be considered as a new ceramic instrumental material with the high-speed cutting characteristics improved considerably. There are several ways of further improvement of performance of Cr_2O_3-based ceramics, mostly directed to the microstructure features, such as nanoscale grains.

Table 4 presents the comparison of overall performance of different cutting tools in turning operations without cooling at cutting speed v_c = 104 m/min and feed f = 0.5 mm/rev. The machined material was steel 30ХГСА (Russian nomenclature), similar to 4130 (USA) and 25CrMo4 (Germany) of hardness HRC 58, and the materials of cutting tools inserts were typical ceramics of the same class.

The data in Table 4 demonstrates that virtually all tested parameters were better in case of Bichromit-R. Number of passes and total working time was almost twice better, and wear of the tool’s back surface was smaller. As a result, roughness of the machined surface was better.

The abovementioned results are mainly attributed to the high fracture toughness discussed in the section 3.1, ensured by the specific sintering technology at smaller temperature and shorter times. It can be assumed that the nanoscale grains of the composite are mainly responsible for the limited crack propagation and unusually high fracture toughness of a ceramic material.

3.5. Physical background

On order to assess the wear of tested cutting tools, the back wear criterion was applied. In case of Bichromit-R, it was h = 0.4 mm. Photomicrographs of the worn tool surface are presented in Figure 6. Like in the surface after the fracture test (Fig 2, left), in the worn surface of the tool submicron structure is clearly seen. Microcracks observable in the micrograph (Fig. 6, right) seem do not develop into large cracks because of nanodispersed structure of material.

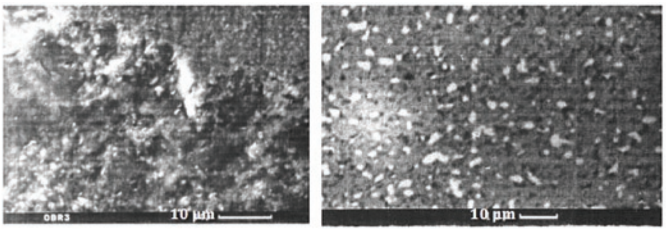

Fig. 6. Microphotographs of the worn surface of the Bichromit-R ceramics (left), and the formation of microcracks at the grain boundaries (right)

Comparative studies of various cutting ceramic materials show that the main reason behind the high wear resistance of Bichromit-R and oxide-carbide ceramics in the processing of steels is the fine-grained structure with submicron elements. Another important feature improving wear resistance is the substructural and dispersed hardening mechanism.

In white Al_2O_3 ceramics, grains do not contain dislocations, which means that grains are not capable to the storage of deformation energy. As a result, micro-destruction of Al_2O_3 grains occurs in the surface layers of the tool. After crack propagation, macroscale wear takes place. This process is slowed down in Bichromit-R due to the features of grain structure.

4. Conclusion

Presented results of the researches demonstrated prolonged durability, higher cutting speeds, smaller wear and better overall performance of cutting tools made out of high-density Cr_2O_3 with some additives AlN, sintered at lower temperatures for a shorter time than usual. Substantial improvement of exploitation characteristics can be attributed to the obtained nanoscale grains inside the bulk material, that are responsible for the increased fracture toughness of a ceramic material, otherwise brittle. Compared to other cutting tools of the same class, Bichromit-R performed the same lifetime for 3-5 times higher cutting speeds, or up to 45% longer lifetime for the same cutting speed.

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Table 4. Comparative tests of different instrumental materials during machining of the steel 30ХГСА, HRC 58

No.	Cutting insert	Number of passes	Total time	Obtained roughness, Ra	Wear of the tool’s back surface, mm	Comment on operation
1	ВОК60	11	63	1.25	0.2	Red spiral cutting chip
2	Valenite (USA)	11	63	0.8	0.15	Red spiral cutting chip
3	Hard alloy ВК6-ОМ	5	31.5	2.5	3	squeal, sparking, crumbling
4	Bichromit-R	20	118	0.63	0.1	Red spiral cutting chip after the 15th pass

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Edvin GEVORKYAN
Department "Quality, standardization, certification
and manufacturing technology of products"
Ukrainian State University of Railway Transport
Square Feyerbach 7, Kharkov, 61010, Ukraine

Mykola PROKOPIV
Bakul Institute for Superhard Materials,
National Academy of Sciences of Ukraine
2, Avtozavodskaya Str., Kiev, 04074, Ukraine

Mirosław RUCKI
Dmitrij MOROZOW
Faculty of Mechanical Engineering,
Kazimierz Pulaski University of Technology and Humanities in Radom
ul. 54 Stasieckiego, 26-600 Radom, Poland

E-mail: edsgev@gmail.com, keramtex@ukr.net, m.rucki@uthrad.pl,
m.rucki@uthrad.pl