Durability and exploitation performance of cutting tools made out of chromium oxide nanocomposite materials

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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], as well as computer simulation methods [13]. In another reported study, Al2O3 was coated on the surface with carbide tools are coated [3], but also ceramic materials are coated in the amount of Eu2O3 decreases the bulk density and wear resistance of ceramics, and 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].

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 Eu2O3 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 Cr2O3 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...
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 Al2O3, SiC, B4C, MoSi2, 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].

Sintering processes typically use high-density Cr2O3 for cutting tools inserts [27]. The chromium oxide (Cr2O3) has a crystalline structure similar to Al2O3, but it performs slightly higher microhardness 29 GPa compared to Al2O3 (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 Cr2O3 for cutting tools inserts was sintered using typical techniques, obtained phase composition of bulk material differed substantially: the sample sintered at T=1500 °C had additional dark phase (marked T3 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.

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 Cr1.4-Al0.6O3, while the dominant substance in the grey phase was chromium oxide Cr2O3.

### Table 1. Distribution of Cr, Al, O in samples of Cr2O3 – 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 |

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 IIIX-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 30XTC (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 (~68 HRC) and tool steel (~68 HRC).

Hard types of cast irons include white cast iron (~50 HRC) and ADI/ Kynemite (~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 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 Cr2O3, 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 KIc obtained for different materials typically used for cutting tools inserts manufacturing. Material Bichromit-R performed KIc above 9 MPa m3/2 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...
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 (Al₂O₃-TiC), produced by NTK. This material is designed and recommended for cutting of hardened steels up to HRC65. In the tests, the steel 5XНМ (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.

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 ВОК-71 (Russian nomenclature).

The measure of the wear is the overall path length $L$ of the cut material during machining, before the destruction of the blade. Significantly, the path length $L = 20,000$ 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 $L = 15,000$ 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.
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 Cr₂O₃ 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 Cr₂O₃-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.

Table 4. Comparative tests of different instrumental materials during machining of the steel 30XTCa, 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   | BOK60          | 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 BK6-0M | 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 |

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.
Table 3. Steady state availability versus δ for Case 2

| δ   | MMM | DDD | DDW | WWD | WWW |
|-----|-----|-----|-----|-----|-----|
| 0.0 | 0.8312 | 0.8829 | 0.8829 | 0.8652 | 0.8652 |
| 0.1 | 0.8228 | 0.8774 | 0.8756 | 0.8519 | 0.8501 |
| 0.2 | 0.8152 | 0.8724 | 0.8688 | 0.8398 | 0.8362 |
| 0.3 | 0.8082 | 0.8678 | 0.8627 | 0.8288 | 0.8235 |
| 0.4 | 0.8017 | 0.8636 | 0.8571 | 0.8187 | 0.8119 |
| 0.5 | 0.7958 | 0.8597 | 0.8519 | 0.8095 | 0.8013 |
| 0.6 | 0.7903 | 0.8562 | 0.8472 | 0.7936 | 0.7916 |
| 0.7 | 0.7852 | 0.8529 | 0.8427 | 0.7866 | 0.7827 |
| 0.8 | 0.7805 | 0.8498 | 0.8386 | 0.7803 | 0.7746 |
| 0.9 | 0.7761 | 0.8470 | 0.8348 | 0.7746 | 0.7672 |
| 1.0 | 0.7719 | 0.8443 | 0.8313 | 0.7603 | 0.7603 |

| δ   | MMM | DDD | DDW | WWD | WWW |
|-----|-----|-----|-----|-----|-----|
| 2.0 | 0.6462 | 0.7154 | 0.7154 | 0.6888 | 0.6888 |
| 3.0 | 0.5123 | 0.5717 | 0.5717 | 0.5479 | 0.5479 |

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