STUDY IN DURABILITY OF CR$_2$O$_3$-BASED CERAMIC CUTTING TOOLS

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Abstract. The research was performed in the context of feasibility examinations of chromia application as cutting tool materials. In the paper, a study on the Cr_2O_3 –based ceramic cutting tools is presented from the perspective of structural features and durability under various machining parameters. Comparative analysis was performed using alumina-based ceramic cutting inserts. Microstructure was examined using scanning and transmission electron microscopy (SEM and TEM), LEO1455 VP (ZEISS) and MIRA3 TESCAN, respectively. It was found that Cr_2O_3 –based ceramic with AlN additions after electroconsolidation exhibited more fine structure with evenly distributed AlN inclusions and small amount of spherical pores, below 2%. The cutting durability tests were performed with both hardened NC11LV and non-hardened C45 (1.0503) steels, using multiedge cutting inserts of dimensions 14.75 mm × 14.75 mm × 4.75 mm, made of respective ceramics. The machine tool Mazak QTE was used for the tests, and the wear criterion was 0.4 mm notch wear value, assessed with Keyence microscope. It was demonstrated that a pure alumina cutting tool exhibited 3 times larger wear than Cr_2O_3–AlN one after 25 minutes of work. On the other hand, Cr_2O_3–AlN cutting edge reached the same wear rate at 175 $m \cdot min^{-1}$ as Al_2O_3 –based tools at just 50 $m \cdot min^{-1}$. For the same cutting speed of 150 $m \cdot min^{-1}$, the chromia-based ceramic insert worked over 30 minutes, two times longer than alumina ones. The increased wear resistance and durability can be attributed to the fine-dispersed structure obtained not only by certain proportion of components, but also by the electroconsolidation technique with specific parameters.

Keywords: sintering, electroconsolidation, ceramics, cutting tools, durability.

Introduction

Nowadays, in the context of the increasing quality demands, development of new cutting tools with improved performance is highly motivated. In industry, superhard materials are widely used for fabrication of cutting tools [1]. Among the hardest materials, cubic boron nitride (cBN) is known, which is inferior only to diamond [2]. However, cBN tools are brittle, easily chipped, not stable at higher temperatures, and thus, cannot withstand higher speeds, and they are expensive [3].

During the cutting process, both machining parameters and tools should be optimised due to the machining-induced physical effects that affect the surface integrity of the machined part [4]. Quality of the finished surface is crucial for its frictional properties [5-6] and is highly dependent on the machining conditions [7-8]. It is also known that high temperature and other severe conditions at the interface between the cutting edge and chip are the main reasons for wear and failures of ceramic tools [9]. Thus, due to continuous development of engineering materials and the increasing demand for machining motivates to continue research and especially to investigate new materials for cutting tools [10].

In the present study, a novel electroconsolidation technology was applied for sintering of Cr_2O_3 – based ceramic cutting tools. It is widely known that Cr_2O_3 is widely applied in industry, especially in form of coatings that provide protection against wear, both sliding and abrasive ones [11]. It was experimentally demonstrated that the friction couples chromia–steel exhibited the lowest seizure loads compared to the steel-steel and WC-steel ones, and the surface did not show significant sliding wear [12]. Thus, it seemed promising to investigate the behavior of Cr_2O_3 matrix composite for cutting tools application and to compare it to alumina-based ones.

The paper presents results of the durability and wear resistance tests of as-prepared cutting inserts in comparison with Al_2O_3 and Al_2O_3 – TiN cutting tools.

Materials and methods

The compaction of samples of the powders was performed using an original vacuum hot-pressing unit. The method employed alternating current as the sole heat source, when passing through the mold and the sample itself. It was described in detail in [13]. The method can be classified as a Field Activated

DOI: 10.22616/ERDev.2023.22.TF054

Sintering Technique (FAST) or Spark Plasma Sintering (SPS), but we prefer the “elecrtoconsolidation” term to emphasize a difference from typical SPS. Compaction of the initial powders of preferably submicron grain size takes place in relatively low temperatures of 1300-1800 °C, during relatively short time of 2-4 min, under mechanical pressure P = 30-45 MPa. The device is shown in Figure 1a. With this method, cutting inserts were made of chromium oxide Cr_2O_3 with addition of aluminum nitride AlN 15% by mass. The SEM image of the powder mixture is shown in Figure 1b.

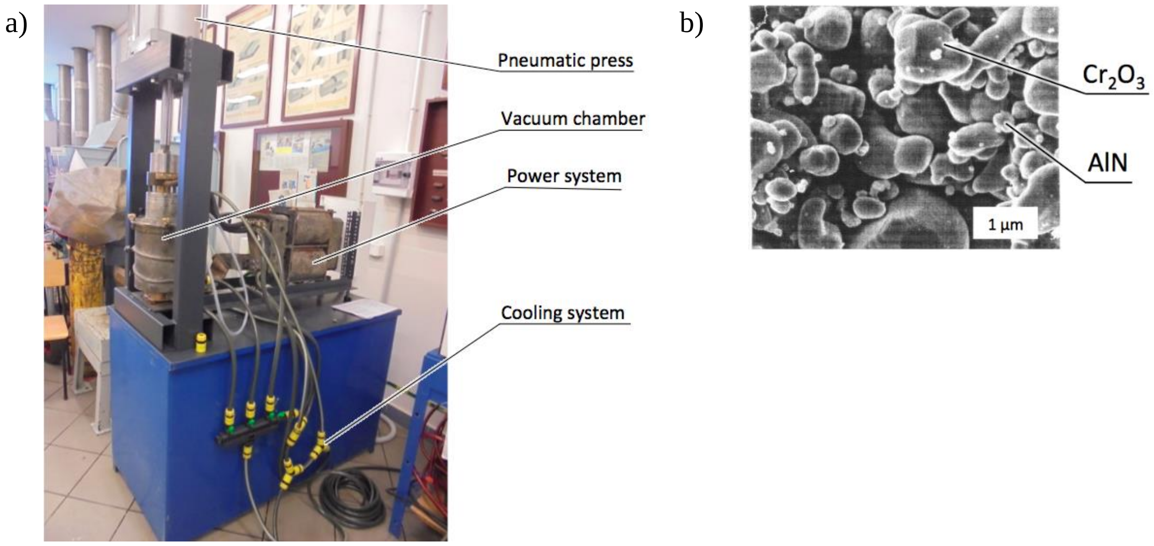

Fig. 1. **Electroconsolidation device (a) and Cr_2O_3-AlN powder mixture (b)**

The inserts of a rounded shape (type R) were made to correspond with the type RNGN 120400 multiedge cutting inserts of dimensions 14.75 mm × 14.75 mm × 4.75 mm. For the purposes of comparative analysis, pure alumina ceramic tools were used (Al_2O_3 > 99% with MgO below 1%), as well as the inserts made of alumina with addition of titanium nitride (ca. 70 wt% of Al_2O_3 and 30 wt% of TiN). The surfaces of the inserts were grinded using a universal grinding machine with special fixation. Grinding wheels were with diamonds of grades 60/40, 20/14, 7/5, 3/2 µm, and water-emulsion coolant was applied.

Microstructures of the powders and samples were examined using scanning and transmission electron microscopy (SEM and TEM), LEO1455 VP (ZEISS) and MIRA3 TESCAN, respectively. The cutting tests for durability and wear resistance of the inserts were performed with both hardened NC11LV and non-hardened C45 (1.0503) steels. The machine tool Mazak QTE was used for the tests, and wear criterion was notch wear of value $VB_N = 0.4$ mm, which was assessed with Keyence microscope.

Results and discussion

According to the available data [14-15], the tested material can be classified as a composite with particulate filler. Dependent on the cutting tool ceramics type, grains of particulate fillers in form of TiC, TiN, ZrO2, Cr3C2, SiC, Cr2N, Cr or other may have different sizes. For instance, in the available material BO13 (Al_2O_3 + MgO), grain sizes of Al_2O_3 are above 3 µm, while reinforcement TiC sizes are between 0.2 and 0.7 µm. In the tested Cr_2O_3 + AlN material, reinforcement particles are somewhat smaller, 0.1-0.5 µm. Also, the proportion by mass of the fillers can be very different. Compared to the available tool ceramics BOK60 (60 wt% Al_2O_3 + 40 wt% TiC), where reinforcement occupies ca 40% by mass, our Cr_2O_3 –based composite had the proportion of AlN reinforcement 15% only. Figure 2a presents the SEM image of the fraction surface of the tested Cr_2O_3 –based ceramic.

It should be noted that the grain dimensions are roughly of micron size, which is favourable for the mechanical strength and other properties. The fracture character in larger grains was transcrystalline, while the particles of Cr and Cr_2N exhibited rather intercrystalline fracture type. Figure 2b illustrates homogenous distribution of the reinforcement throughout the volume of the tested composite.

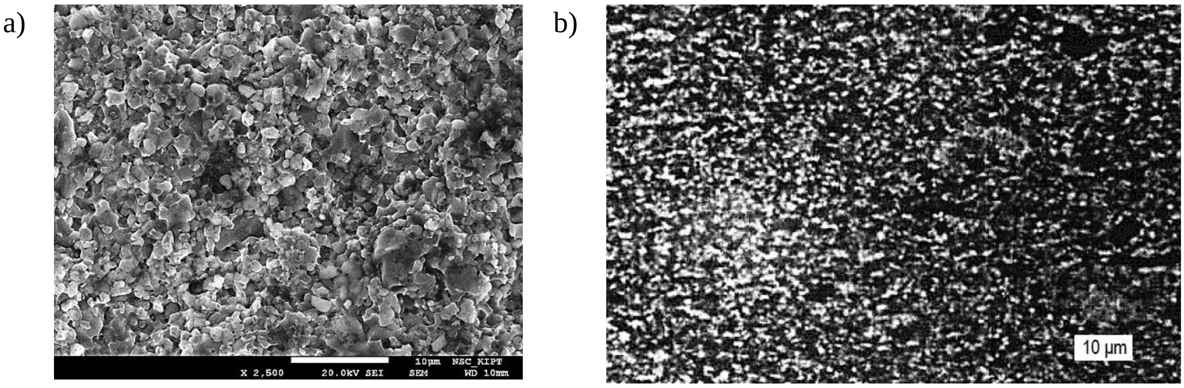

Fig. 2. **Surface of Cr_2O_3-AlN ceramic: a – after fracture test; b – after diamond grinding**

Analysis of the grinded surface revealed presence of microcracks of the depth 2-5 μm. Moreover, presence of the residual stresses of significant values was found under the surface layer. Porosity of the tested material did not exceed 2%. The pores had mostly spherical form, which contributed to the decrease of the residual stresses. It can be concluded that the grinding process had initiated dislocations in the structure of the newly fabricated Cr_2O_3 + AlN cutting inserts. Later, this process was continued during the cutting test.

Under the severe friction and high temperatures, both the oxide matrix and dispersed nitride filler experienced increase of the dislocation density, which decreased the wear rate. Damage of the Cr_2O_3 + AlN cutting edge is accompanied with microchipping of the grains as a result of increased density of dislocations, up to the critical value. Microcracks appeared in the boundaries between grains, and creep of the material took place with subsequent tear out the parts of the material. It can be assumed that increased wear resistance may be explained by the small grain sizes and by the presence of solid solution (Cr, Al)$_2$O$_3$ in the interfacial areas between the phases [16].

Figure 3 illustrates the wear of the cutting edge after the machining test. The test involved hardened steel NC11LV of hardness ca. HRC 59, turned at speed v_c = 100 m·min^{-1} with feed f_n = 0.085 mm per rotation and cutting depth a_p = 0.2 mm.

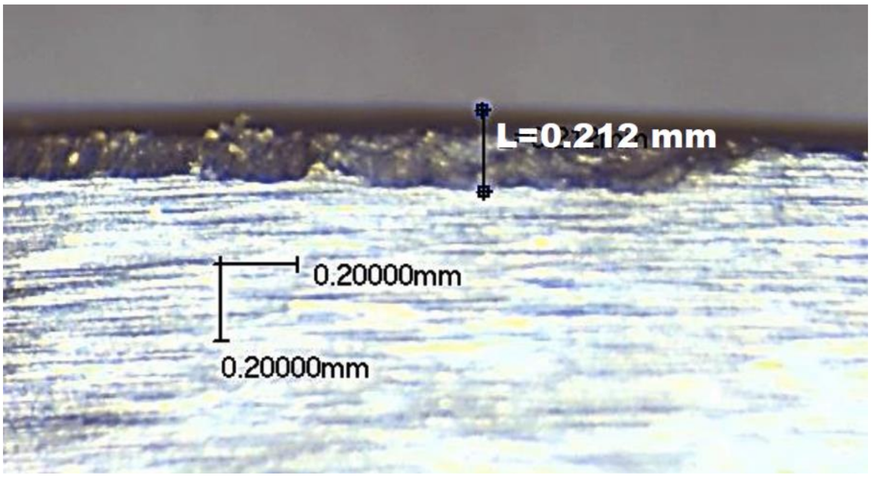

Fig. 3. **Worn edge of the cutting tool made of ceramic**

The experiments with machining of NC11LV steel hardened up to 59 HRC exhibited significant increase of the working time of the tested cutting tools before the critical wear was reached. It is seen in Fig. 4 that at smaller cutting speeds, the inserts Cr_2O_3 + AlN worked by 40% longer than the Al_2O_3 + TiN tools, while compared to Al_2O_3 + MgO ones, they exhibited 30% longer working time. On the other hand, at higher cutting speeds, the tested inserts worked 100% time longer than the Al_2O_3 + TiN tools, and 50% longer than Al_2O_3 + MgO ones.

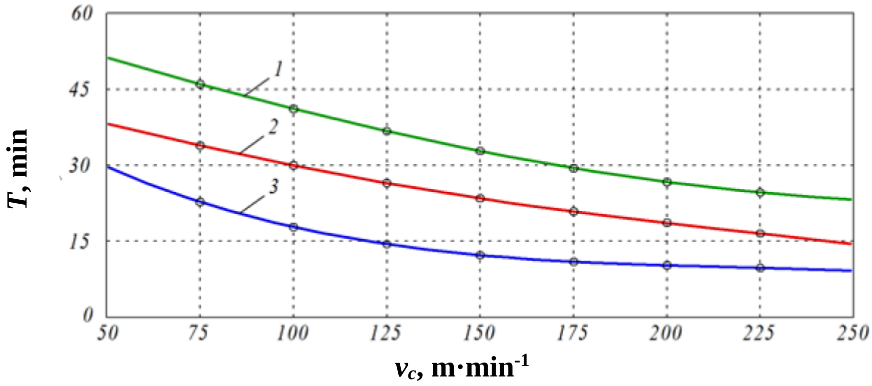

Fig. 4. **Plot of the working time of cutting tools dependent on the cutting speed v_c when turning steel NC11LV at feed f_n = 0.085 mm/rotation ad cutting depth a_p = 0.2 mm. Respective cutting insert materials are denoted as follows:** 1 – Cr_2O_3 + AlN; 2 – Al_2O_3 + TiN; 3 – Al_2O_3 + MgO

Somewhat different dependencies appeared to take place when cutting non-hardened C45 (1.0503) steel. Figure 5 presents the respective plots of working times versus the cutting speed v_c while the feed and cutting depth remained unchanged, f_n = 0.15 mm/rotation and a_p = 0.3 mm, respectively.

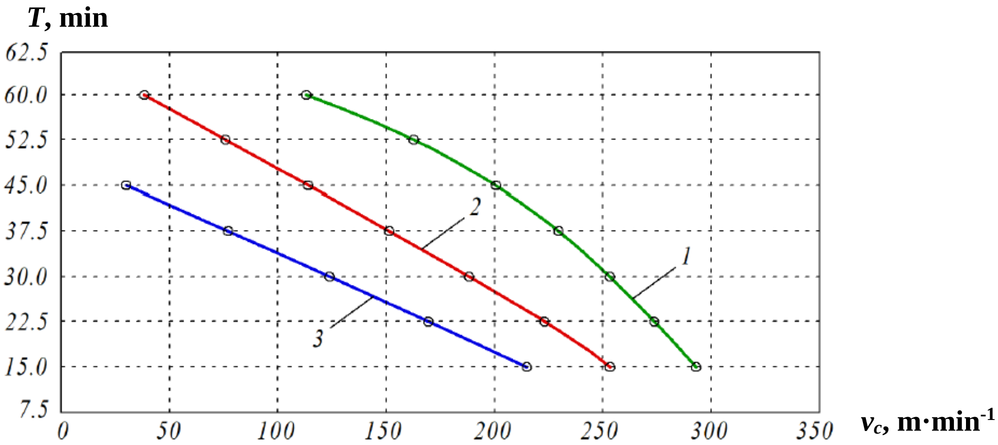

Fig. 5. **Graphs of the working time of the tested cutting tools dependent on the cutting speed v_c when turning steel 45 at feed f_n = 0.15 mm/rotation and cutting depth a_p = 0.3 mm. Respective cutting insert materials are denoted as follows:** 1 – Cr_2O_3 + AlN; 2 – Al_2O_3 + TiN; 3 – Al_2O_3 + MgO

When machining C45 steel, both Al_2O_3 + MgO and Al_2O_3 + TiN cutting tools exhibited almost proportional wear dependence on the cutting speed. Unlike these two curves, the graph (1) representing Cr_2O_3 + AlN is less declining in the initial stage. Only above 200 m·min^{-1} its declination is stronger. Due to this feature, the working time of the Cr_2O_3 + AlN insert was generally about two times longer than that of Al_2O_3 + MgO and by 30% longer than that of Al_2O_3 + TiN. It can be concluded, thus, that the abovementioned small reinforcement grain sizes and dispersion strengthening mechanism contributed to the improvement of the wear resistance of the tested material.

Other perspective can be noted when analysing the notch wear value VB_N graphs showing their changes in time, as shown in Fig. 5. It is seen that after 10 minutes of machining, Al_2O_3 + TiN cutting tools reached two times larger notch wear than the tested Cr_2O_3 + AlN insert, while Al_2O_3 + MgO tool wear was almost 3 times larger. The trend of stable wear of both composite inserts, Al_2O_3 + TiN and Cr_2O_3 + AlN, is similar up to 25 minutes, but after that time the wear rate of Al_2O_3 + TiN cutting edge increases more than that of Cr_2O_3 + AlN.

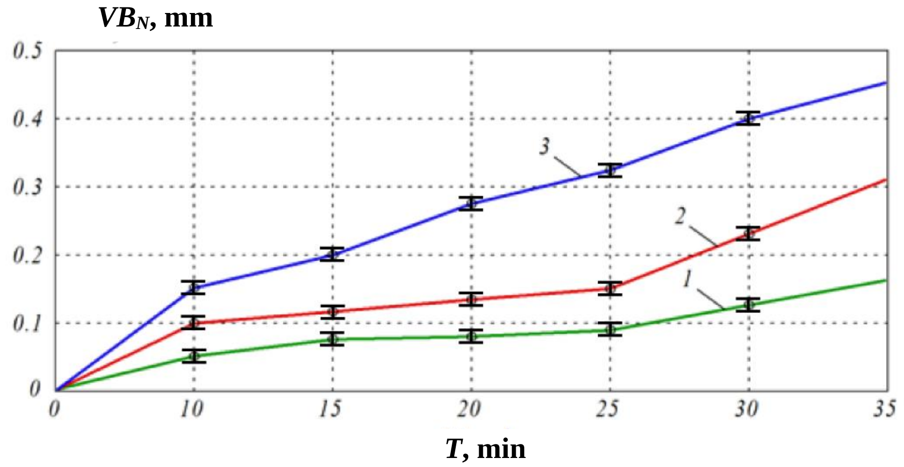

Fig. 5. **Graphs of the notch wear VB_N of the tested cutting tools. Respective cutting insert materials are denoted as follows:** 1 – Cr_2O_3 + AlN; 2 – Al_2O_3 + TiN; 3 – Al_2O_3 + MgO

It should be noted also that the fine-dispersed structure and smaller dimensions of the reinforcement particles in the composite allow for fabrication of sharper cutting edges. A smaller edge radius can obviously provide a higher quality of the machined surface, which was demonstrated with other materials [17].

Conclusions

1. The electroconsolidation technique allowed for fabrication of fine-dispersed ceramic composite for cutting tools.
2. Cr_2O_3 + AlN cutting inserts exhibited much higher wear resistance than Al_2O_3 + TiN and Al_2O_3 + MgO ones. It was confirmed by examining the working time before the critical VB_N value was reached and also checking VB_N at time intervals.
3. It was demonstrated that Cr_2O_3 + AlN cutting inserts performed better than other tested inserts during machining of both hardened and non-hardened steels.

Acknowledgements

The researches were supported by the Polish Ministry of Science and Higher Education for UTH Radom, statutory funds 3257/183/P (DBUPB/2016/009) and by the Ministry of Sciences and Education of Ukraine, grant number ДРН 0121U109441.

Author contributions

Conceptualization, Z.S. and E.H.; methodology, E.H., M.P. and D.M.; software, L.V. and Z.S.; validation, E.H. and M.P.; formal analysis, L.V and M.R.; investigation, Z.S., D.M., V.N. and M.R.; data curation, E.H., L.V. and M.R.; writing – original draft preparation, V.N.; writing – review and editing, D.M. and M.R.; visualization, M.P., V.N.; project administration, D.M.; funding acquisition, Z.S. All authors have read and agreed to the published version of the manuscript.

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