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Cutting properties of the Al_2O_3+$SiC_{(w)}$ based tool ceramic reinforced with the PVD and CVD wear-resistant coatings

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Abstract: The paper presents investigation results of tribological properties of the coatings deposited with the PVD and CVD techniques on cutting inserts made from the Al_2O_3+$SiC_{(w)}$ oxide tool ceramic. Tests were carried out on the multipoint inserts made from the Al_2O_3+$SiC_{(w)}$ oxide ceramics, uncoated and coated with gradient, mono-, multilayer and multicomponent hard wear resistant coatings composed of TiN, TiCN, TiAlN, TiAlSiN and Al_2O_3 layers with PVD and CVD processes. Substrate hardness tests and microhardness tests of the deposited coatings were made on the ultra-micro-hardness tester.

Keywords: Oxide ceramics; Al_2O_3; SiC; Multi-layer coatings; Multi-component coatings; Gradient coatings; Wear.

1. INTRODUCTION

Machining productivity and quality of the machined workpiece depend, to a great extent, on the properties of tool materials. Ceramic materials with high hardness and high strength in the broad range of working temperatures and with low abrasion wear, with the Al_2O_3 based ones among them, are used more and more often for cutting tools. The Al_2O_3 oxide ceramics, as mentioned by the Author of the reviewed thesis, is characteristic of high hardness, compression strength at the cutting temperature above 1000 ^{o}C, and the best – compared to other tool materials – chemical wear resistance; however having high brittleness and low thermal shock resistance. These drawbacks are compensated in part by using the TiC

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additions and the SiC whiskers. Whiskers with the following parameters: thickness d = 0.1-0.5 μm and slenderness ratio l = (5-10) d, are introduced into the tool ceramics. Ceramics with whiskers are obtained mostly by the isostatic hot sintering and by the uniaxial hot pressing. The increase of the whiskers portion to 15-20% causes increase of the ceramics strength. Further increase of the SiC whiskers portion deteriorates the mechanical properties because of the increased probability of the development of whiskers agglomerates, featuring the cracking propagation source. A factor affecting the selection of the optimum portion of the SiC phase in the sinter is the decrease of the sinter density along with the growth of the whiskers portion leading to material hardness deterioration, which in case of the material used for cutting tools, is a significant limitation of possibility of its application. Introducing whisker to the oxide ceramics results in their hardness increase, improvement of their crack resistance and bending strength. Tools containing the SiC whiskers have the life exceeding other tool materials even by 300%, allowing at the same time very high cutting speeds. One of the disadvantages of the reinforced ceramics is decay of whiskers in case of machining alloys containing iron, which significantly limits its use. In connection with the unsatisfactory attempts to introduce the SiC whiskers to oxide ceramics and serious limitations in its use, the research is conducted on the possibility of improvement of properties of these materials by employment of the surface layers [1-9].

The goal of this paper has been investigation of properties of the Al_2O_3+$SiC_{(w)}$ based oxide tool ceramics coated with the anti-wear gradient, mono-, multilayers and multicomponent of the TiN, TiAIN, TiN+TiAlSiN+TiN, TiN+multiAiAlSiN+TiN and TiN+TiAlSiN+ AlSiTiN types in the cathode arc evaporation CAE-PVD and with the multi-layers of the TiCN+TiN and TiN+Al_2O_3 types obtained in the chemical deposition from the gas phase CVD process.

2. EXPERIMENTAL PROCEDURE

The investigations were carried out on the multi-point inserts made from the Al_2O_3+$SiC_{(w)}$ oxide ceramics uncoated, coated in the PVD and CVD processes with thin coatings. The inserts were gradient, mono-, multilayer and multicomponent coated in the PVD process – Cathodic Arc Evaporation (CAE) and CVD process. Specifications of the investigated materials are presented in Table 1.

Table 1.
Specifications of the PVD and CVD coatings put down on the Al_2O_3+$SiC_{(w)}$ oxide ceramics.

Material type	Composition	Coating thickness, μm	Process type
Al_2O_3+$SiC_{(w)}$ oxide ceramics	TiN	0.9	PVD
	TiN+TiAlSiN+TiN	2.5	PVD
	TiN+multiTiAlSiN+TiN	2.8	PVD
	TiN+TiAlSiN+AlSiTiN	2.5	PVD
	TiAlN	2.8	PVD
	TiCN+TiN	2.6	CVD
	Al_2O_3+TiN	7.9	CVD

Examinations of coatings' thicknesses were made using the "kalotest" method, consisting in the measurement of the characteristic dimensions of craters developed on the examined specimen surface with a coating. The measurements were made on the device developed in house. In addition, to verify the obtained results, measurements of the coatings were made also on the scanning electron microscope on the fractures perpendicular to their free surfaces.

The microhardness tests of coatings were made on the SHIMADZU DUH 202 ultra microhardness tester. Test conditions were selected so that the required and comparable test results would be obtained for all analyzed coatings. Measurements were made at 0.07 N load, eliminating influence of the substrate on the measurement results.

Adhesion evaluation of the coatings on the investigated inserts was made using the scratch test on the CSEM REVETEST device, by moving the diamond penetrator along the examined specimen's surface with the gradually increasing load. The tests were made with the following parameters: load range 0-100 N, load increase rate (dL/dt) 100 N/min, penetrator's travel speed (dx/dt) 10 mm/min, acoustic emission detector's sensitivity AE 1. The critical load L_C, at which coatings' adhesion is lost, was determined basing on the registered values of the acoustic emission AE.

Cutting ability of the investigated materials was determined basing on the technological continuous cutting tests of the KGR-Nl-400 spheroidal cast iron with the hardness of about 165 HV. The VB=0.30 mm width of the wear band on the surface of the tool used for machining was the criterion of the cutting edge consumption evaluation. Cutting tests of the investigated Al_2O_3+$SiC_{(w)}$ based tool oxide ceramics – uncoated and coated – were carried out as the continuous turning without the use of cutting fluids on the numerically controlled MORI SEIKI model Sl 153 machine tool. The following parameters were used in the machining capability experiments: feed rate f=0.20 mm/rev, depth of cut a_p=2 mm, cutting speed v_c=250 m/min. The character of the developed failure was evaluated basing on observations on the light microscope and on the scanning electron microscope. In case of the uncoated tools the test was continued until the wear criterion was reached; however, the test period for the coated tools was never shorter than in case of the uncoated tools, which makes it possible to compare the wear band width VB after reaching the wear criterion by the uncoated test piece. Measurements of the VB values with the accuracy of up to 0.01 mm were carried out using the Carl Zeiss Jena light microscope at the magnification of 14x. Photos of the cutting inserts' flank and face at various wear stages were made on LEICA MEF4A light microscope at the magnification of 10x, and on the JEOL JSM - 5610 scanning electron microscope using magnifications of 95÷1100x. The examination results were presented as plots of the relationship of the wear band VB on tool flank versus test duration, at the particular experiment conditions.

Investigations of surface roughness of KGR-Nl-400 spheroidal cast iron in machinability test were made on device SURTRONIC 10 TAYLOR-HOBSON.

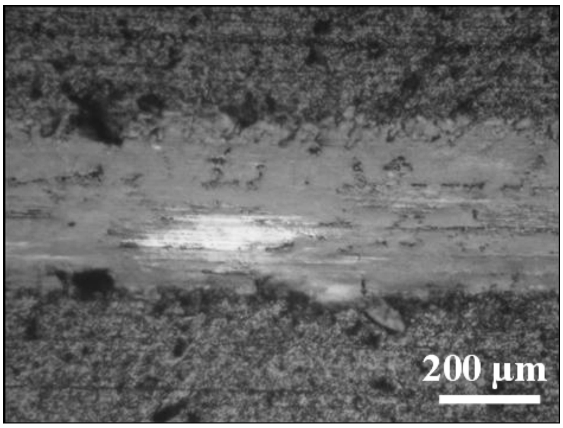
3. DISCUSSION OF INVESTIGATION RESULTS

The Al_2O_3+$SiC_{(w)}$ ceramics microhardness is 1870 MPa and grows significantly after deposition of the PVD and CVD coatings, except the TiCN+TiN coating. The maximum microhardness of $HV_{0.07}$=40.2 GPa was observed in case of the TiN+multi TiAlSiN+TiN PVD coating deposited onto the Al_2O_3+$SiC_{(w)}$. ceramics substrate. Over 80% increasing of microhardness value is also observed after depositing of TiAlN PVD coating and TiN+Al_2O_3 CVD coating (Table 2). No relationship was found out between the substrate hardness and hardness of the deposited coating, which confirms the proper selection of the maximum load F_{max}=0.07 N to eliminate the influence of the substrate hardness on the measurement result.

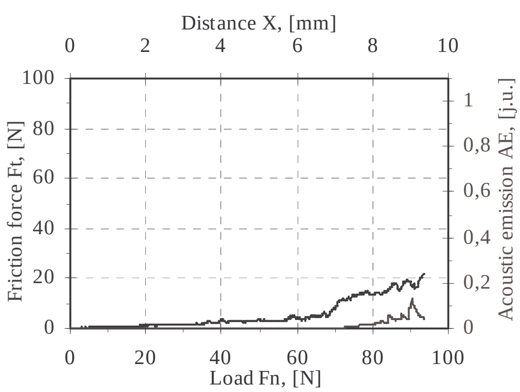
The TiN+TiAlSiN+TiN coating demonstrates the highest critical load value L_c=70 N measured by the acoustic emission registration (Fig. 1, Table 2). No sudden increase of the acoustic emission was registered in case of the TiAlN coating; however, the metallographic observations make it possible to determine optically the critical load of $L_{c(opt)}$=99 N. In case of TiN+multiTiAlSiN+ TiN coating the first coating failure symptoms are the conformal cracks resulting from tension, turning into single spallings located at the bottom of the developing crevice and in the coating-crevice contact zone. Chipping and spalling failures develop in the central zones of the crevices and at their edges in the form of the fine arc-shaped craters. Similar effects can be observed at the edges in the ending part of the crevice. Single failures are often connected forming bands of the local coating delamination, not more. Semicircles connected with the conformal cracking occur at the crevice bottom at the big load force, attesting the fragmentation, local delamination, and consequent relocation of the torn coating fragments along with the plastic strain of the substrate by the traveling indenter.

It was found out, basing on the repeated technological turning test of grey cast iron with the Al_2O_3+$SiC_{(w)}$ ceramics, that the tool reaches the VB=0,30 mm wear criterion after t=7.8 min cutting time. Time of t=7.8 min was assumed as the comparative criterion for measurement of the wear band width for all specimens with the Al_2O_3+$SiC_{(w)}$ substrate After the assumed machining test duration the smallest cutting tool flank wear band width of VB=0.13 mm was revealed in case of the TiN+Al_2O_3 CVD coating (Fig. 3), and the biggest cutting tool flank wear band width of VB=0.28 mm was revealed in case of the TiN PVD coating. It was found out, thanks to the metallographic analysis carried out on the scanning electron microscope, that the tribological defect types occurring most often, identified in the investigated materials are as follows: mechanical defects and abrasive wear of the tool flank, development of the crater on tool face, thermal cracks on tool flank, spalling of the cutting edge, and build-up edge from the chip fragments (Fig. 2).

Basing on the roughness tests of the machined material, depending on the cutting period, it was found out that depositing the PVD and CVD coatings (except TiN, TiAlN and TiN+Al_2O_3 coatings) onto the Al_2O_3+$SiC_{(w)}$ oxide tool ceramics results in decrease of the machined material roughness and – the same – improvement of its quality, especially at the final machining process stage. From all the investigated materials, the minimum roughness of R_a=1.13 μm at the final machining stage was revealed in case of the TiN+multiTiAlSiN+TiN coating deposited onto the Al_2O_3+$SiC_{(w)}$ ceramics substrate. In case of all coatings the roughness of R_a parameter at the final machining stage is below 2.5 μm so the quality of machined material can be described as high.



a)



b)

Figure 1. a) Indenter trace with the optical L_c load, b) scratch test results of the TiN+TiAlSiN +TiN coating surface deposited on Al_2O_3+$SiC_{(w)}$ substrate

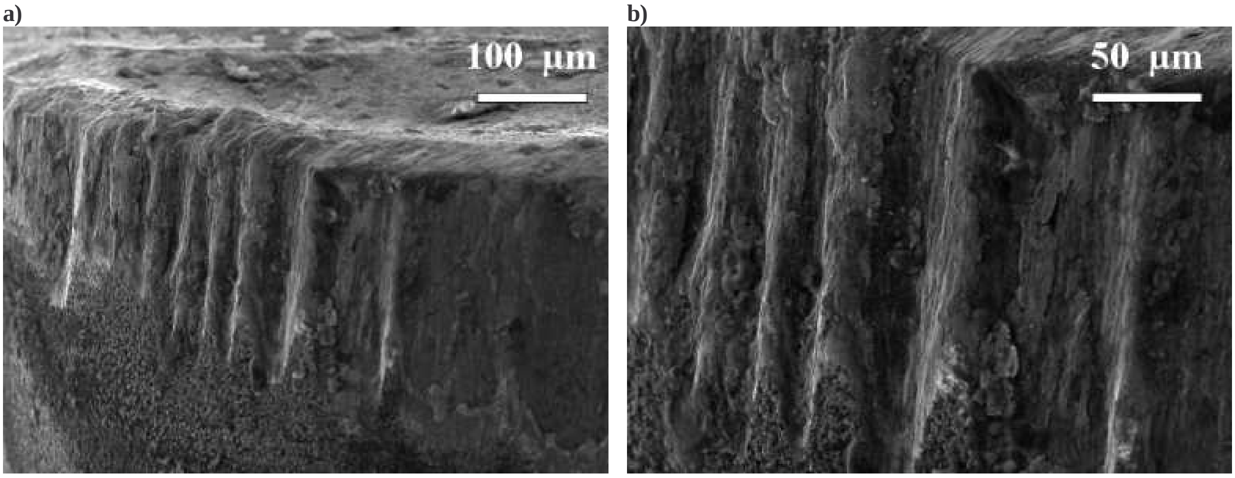


Figure 2. a) Character of wear of the Al_2O_3+$SiC_{(w)}$ sample with TiN+Al_2O_3 coating, investigated with SEM after cutting test, b) the detail of Figure a)

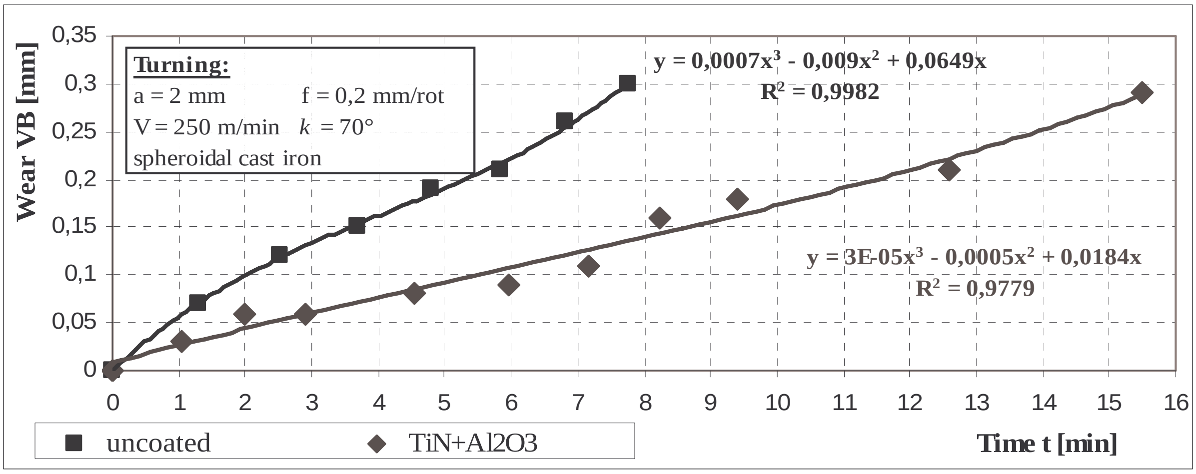


Figure 3. Comparison of the approximated values of the VB wear of the Al_2O_3+$SiC_{(w)}$ based ceramics: uncoated and coated with the CVD TiN+Al_2O_3 coating, depending on machining time

Table 2.
Comparison of mechanical and functional properties of uncoated and coated Al_2O_3+$SiC_{(w)}$ tool ceramics.

Coating	Process type	Microhardness $HV_{0.07}$, MPa	Critical load L_c, N
-	-	1870	-
TiN	PVD	2780	38_{opt}
TiN+TiAlSiN+TiN	PVD	2480	70
TiN+multiTiAlSiN+TiN	PVD	4020	58
TiN+TiAlSiN+AlSiTiN	PVD	2380	80_{opt}
TiAlN	PVD	3370	99_{opt}
TiCN+TiN	CVD	2270	40
Al_2O_3+TiN	CVD	3670	18

4. CONCLUSION

The Al_2O_3+$SiC_{(w)}$ ceramics microhardness grows significantly after deposition of the PVD and CVD coatings. Over 110% increasing of microhardness value is also observed after depositing of TiN+multiTiAlSiN+TiN PVD coating, over 80% increasing of microhardness value is observed after depositing of TiAlN PVD coating and TiN+Al_2O_3 CVD coatings. The TiN+TiAlSiN+TiN coating demonstrates the highest critical load value L_c=70 N measured by the acoustic emission registration but in case of TiAlN coating L_c value was determined optically and achieved 99 N. All the coatings put down demonstrate good adhesion to the substrate. The tribological defect types occurring most often, identified in the investigated materials during the technological cutting tests are the mechanical defects and abrasive wear of the tool flank, development of the crater on tool face, thermal cracks on tool flank, spalling of the cutting edge, and build-up edge from the chip fragments. Depositing the PVD and CVD coatings onto the Al_2O_3+$SiC_{(w)}$ oxide tool ceramics results in the significant increase of the tool life and in lowering the roughness parameter value for the machined material, and finally in improvement of its quality, especially at the final machining process stage.

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