

M. STASZUK*, L.A. DOBRZAŃSKI*, T. TAŃSKI*, W. KWAŚNY*, M. MUSZTYFAGA-STASZUK*

THE EFFECT OF PVD AND CVD COATING STRUCTURES ON THE DURABILITY OF SINTERED CUTTING EDGES

WPLYW STRUKTURY POWŁOK PVD I CVD NA TRWAŁOŚĆ SPIEKANYCH OSTRZY SKRAWAJĄCYCH

In the work it was demonstrated that the exploitative stability of edges from tool ceramics and sintered carbides coated with gradient and multilayer PVD and CVD coatings depends mainly on the adherence of the coatings to the substrate, while the change of coating microhardness from 2300 to 3500 HV0.05, the size of grains and their thickness affect the durability of the edges to a lesser extent. It was found that some coatings showed a fine-grained structure. The coatings which contained the AlN phase with hexagonal lattice showed a considerably higher adhesion to the substrate from sialon ceramics rather than the coatings containing the TiN phase. Better adherence of the coatings containing the AlN phase with hexagonal lattice is connected with the same kind of interatomic bonds (covalent) in material of both coating and ceramic substrate. In the paper the exploitative properties of the investigated coatings in the technological cutting trials were also determined. The models of artificial neural network, which demonstrate a relationships between the edge stability and coating properties such as: critical load, microhardness, thickness and size of grains were worked out.

Keywords: Tool Materials, PVD and CVD coatings, Surface Treatment, Machining, Artificial Neural Network

W pracy wykazano, że trwałość eksploatacyjna ostrzy skrawających z ceramiki narzędziowej i węglików spiekanych pokrytych gradientowymi i wielowarstwowymi powłokami PVD oraz CVD zależy głównie od przyczepności powłok do podłoża, natomiast zmiana mikrotwardości w zakresie od 2300 do 3500 HV0,05, wielkości ziarn oraz ich grubości w mniejszym stopniu wpływają na trwałość ostrzy. Powłoki wykazują drobnoziarnistą strukturę. Powłoki zawierające fazę AlN o sieci heksagonalnej wykazują lepszą przyczepność do sialonowego podłoża niż powłoki zawierające fazę TiN. Lepsza przyczepność powłok zawierających fazę AlN o sieci heksagonalnej związana jest z takim samym rodzajem wiązań międzyatomowych (kowalencyjnych) w materiale powłoki i ceramicznego podłoża. W pracy określono także własności eksploatacyjne powłok w technologicznej próbie toczenia. Zależności pomiędzy trwałością ostrza a własnościami powłok takimi jak obciążenie krytyczne, mikrotwardość, grubość i wielkość ziarna określono z zastosowaniem sztucznych sieci neuronowych.

1. Introduction

Numerous research studies have been devoted recently to coated tool materials, including also coated tool ceramics. It has been demonstrated that the designing of the coating-cutting edge system is based on such a selection of coating material which would reduce or totally eliminate the dominating wear mechanism of the cutting edge. As it has been demonstrated by numerous research studies, the coating should satisfy many requirements to ensure an appropriate protection of the tool during the machining. Literature studies show that the most important properties of coatings determining their exploitative advantages include undoubtedly microhardness, adhesion to substrate, thickness and grain size. Therefore, the paper has been focused on the research aiming to estimate the influence of coating properties of the coated cutting edges [1-11].

The application of systems supporting the design process is a necessity to be followed in our current economy. The

increase of computing power observed over the last years contributes to the development of modern information technology tools applied to improve the quality of a product and to reduce its price. A special attention has been given to the systems developed for several years based on artificial intelligence algorithms and used to predict exploitative properties of the manufactured cutting edges on the basis of coating properties applied on sintered cutting edges. It can provide the manufacturers of cutting edges with the knowledge involving the exploitative durability of coated cutting edges without the necessity to repeat the expensive and long-lasting cutting ability trials. The capability to model the properties of materials is therefore extremely valuable for the manufacturers and designers of modern cutting tools since it means that the requirements of customers involving the quality of the delivered products can be satisfied. The modeling of coating properties is also connected with financial advantages since the expensive and time consuming research is reduced to a necessary minimum, that is to the research indispensable to

* DIVISION OF MATERIALS PROCESSING TECHNOLOGY, MANAGEMENT AND COMPUTER TECHNIQUES IN MATERIALS SCIENCE, INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS, SILESIAN UNIVERSITY OF TECHNOLOGY, 18A KONARSKIEGO STR., 44-100 GLIWICE, POLAND

TABLE 1

Mean values of thickness, microhardness, critical load, grain size and cutting ability of investigated samples

Substrate	Coating	Thickness, μm	Micro-hardness, HV 0.05	Critical load L_c , N	Grain size, nm	Cutting ability T, min
Sintered carbides	uncoated	-	1826	-	-	2
	Ti(B,N)	1.8	2951	34	21	15
	(Ti,Zr)N	3.0	2842	40	21.4	13
	Ti(C,N) (1)	2.1	2871	49	17.7	13
	Ti(C,N)+(Ti,Al)N	2.8	3076	39	16.5	15
	Ti(C,N) (2)	2.1	3101	77	13.5	53
	(Al,Ti)N	2.5	3301	100	9.8	55
	(Ti,Al)N	3.5	3327	109	20.9	60
	(Al,Cr)N	3.8	2867	96	27.2	45
	Ti(C,N)+Al ₂ O ₃ +TiN	8.4	2315	93	250.7 ¹⁾	23
					421 ²⁾	
Ti(C,N)+TiN	1.8	2443	110	356 ¹⁾	27	
				294.5 ³⁾		
Sialon tool ceramics	uncoated	-	2035	-	-	11
	Ti(B,N)	1.3	2676	13	57	5
	(Ti,Zr)N	2.3	2916	21	13.6	5,5
	Ti(C,N) (1)	1.5	2872	25	21.3	5
	Ti(C,N)+(Ti,Al)N	1.4	2786	36	24	6
	Ti(C,N) (2)	1.8	2843	26	18.7	9
	(Al,Ti)N	3.0	3600	112	8.2	72
	(Ti,Al)N	5.0	2961	21	40	9
	(Al,Cr)N	4.8	2230	53	16.7	50
	Ti(C,N)+Al ₂ O ₃ +TiN	7.0	2669	43	266.5 ¹⁾	3
					324 ²⁾	
	Ti(C,N)+TiN	1.3	2746	72	332 ¹⁾	15
112 ³⁾						

¹⁾ TiN layer; ²⁾ Al₂O₃ layer; ³⁾ Ti(C,N) layer

It is important that the presented here research ranks the coatings with respect to the exploitative durability of cutting edges made of sintered carbides and sialon ceramics covered with the investigated coatings. The durability of cutting edges (Table 1) made of sialon tool ceramics covered with the investigated coatings is within the range from 5 to 72 minutes of cutting trials of gray cast iron, and the durability of the cutting edges made of sintered carbides with the investigated coatings is within the range from 13 to 60 minutes. It should be also emphasized here that the highest exploitative durability is exhibited by cutting edged made of sialon ceramics covered with the coatings (Al,Ti)N and (Al,Cr)N, and the durability of non-coated sialon cutting edges is 11 minutes. In the case of sintered carbide cutting edges, the highest exploitative durability is exhibited by the inserts coated by (Ti,Al)N and (Al,Ti)N, and the durability of sintered carbide inserts without coating was estimated at 2 minutes of cutting trials.

The critical loading (Table 1) is to a great extent dependent on the applied coating material (chemical composition,

phase composition). The said dependence is particularly evident in the case of PVD coatings on sialon ceramics substrate. The coatings in which only phases TiN and Ti(C,N) are present demonstrate low adhesion to the sialon substrate $L_c = 13 \div 36 \text{ N}$. And the coatings containing the phase AlN are characterized by a very good adhesion to the substrate $L_c = 53 \div 112 \text{ N}$. It should be underlined that sialons belong to covalence ceramics, whereas in the coatings containing isomorphous phases with titanium nitride TiN, metallic bonds occur, which results in low adhesion of these coatings to the substrate of a different bonding. In the case of coatings containing the AlN phase of the hexagonal lattice, there occur covalence bonds, in the analogous manner as in the ceramic substrate, which, in effect, yields good adhesion of these coatings to the substrate. It bespeaks of the fact that the type of interatomic bonds occurring in the material of substrate and coating exerts a great influence on the adhesion of the coatings to the substrate.

The adherence of coatings to the substrate from sintered carbides, apart from adhesion, is also dependent on slight diffusive dislocation of chemical elements in the contact zone, which is the result of the implantation of high-energy ions falling down on the negatively polarized substrates. This has been confirmed by the research results obtained with the application of glow discharge optical spectrometer GDOES (Fig. 2), since the high-energy ions falling down on the polarized substrate bring about numerous phenomena, among others local temperature rise, faster chemisorption, intensification of surface diffusion processes and into the substrate. There may also occur a slight penetration of ions (about several nm) and partial sputtering of atoms of the coating being deposited.

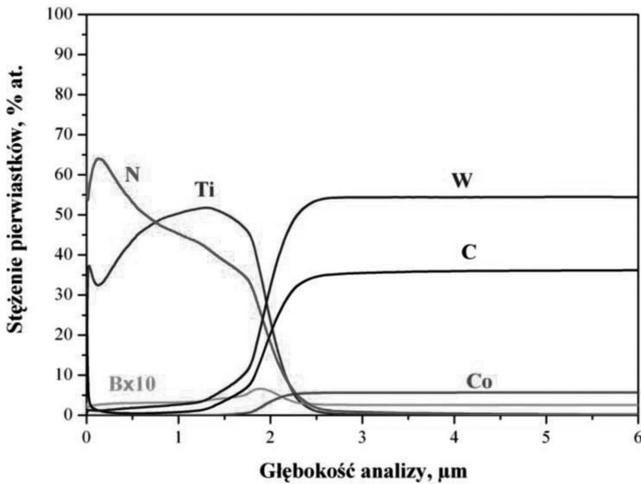


Fig. 2. Changes of constituent concentration of the Ti(B,N) coating and the sintered carbides substrate material

Also the observed structures of thin foils obtained from the investigated coatings bespeak of the fact that the coatings are characterized by high grain-fineness. Furthermore, the diffractive tests on thin foils confirm the presence of isomorphic phases with titanium nitride of the cubic lattice and AlN phase of the hexagonal lattice in the case of (Al,Ti)N coating (Fig. 3).

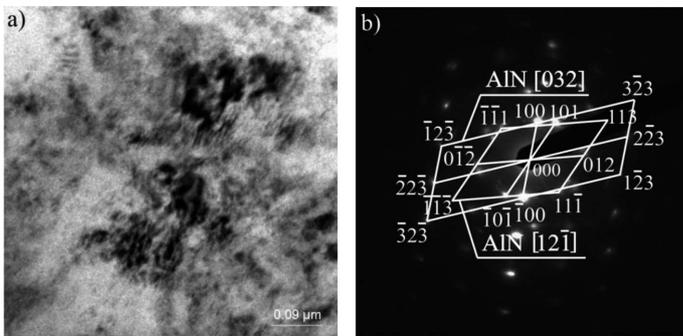


Fig. 3. Structure of the thin foil from the (Al,Ti)N coating: a) bright field; b) diffraction pattern from area a and solution of the diffraction pattern

Basing on the fractographic research it was found that the coatings demonstrate compact structure without pores or non-continuities, similar to the column structure corresponding to zone IV (T) according to Thornton’s model. And the coatings Ti(B,N), (Ti,Zr)N and (Ti,Al)N obtained on sialon

ceramics have the structure of slightly bigger column grains, close to zone II according to Thornton’s model (Fig. 4). Moreover, the particular layers of the multi-layer coatings demonstrate compact structure without delamination or defects and they closely adhere to one another.

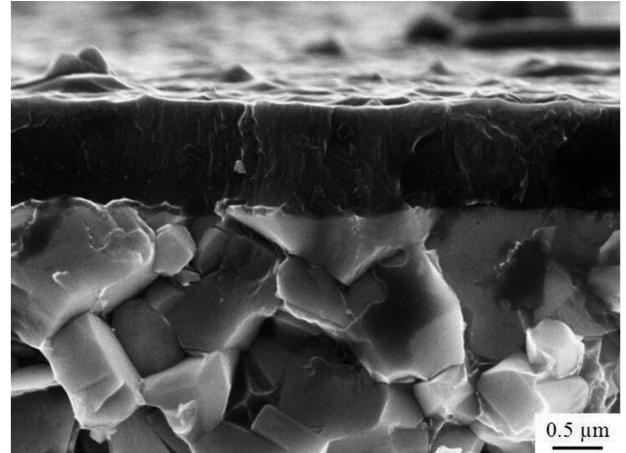


Fig. 4. Fracture of the Ti(B,N) coating deposited onto the sintered carbides substrate

In effect of the microhardness tests it was found that the microhardness range for the coatings obtained on sialon ceramics is within 2315÷3301 HV, and the microhardness range for the coatings obtained on sintered carbides is within 2230÷3600 HV (Table 1).

Basing on the experimental set of results, an artificial neural network was elaborated which allows to determine if there is a dependency between the properties of the coatings such as hardness, adhesion to substrate, grain size or thickness and cutting ability of cutting edges covered by the investigated coatings. The value of mean absolute error, standard deviation and Pearson’s correlation factor for the training, validation and testing sets bespeak of the fact that the applied artificial neural networks correctly reflect the modeled relations (Table 2).

TABLE 2

Regression statistics of artificial neural network trained for prediction of PVD and CVD coatings properties deposited onto sialon ceramics

Network architecture	Regression statistics	Data sets		
		Training Set	Validation Set	Testing Set
MLP3 4:4-6-1:1	Average absolute error	2.57	2.17	2.74
	Standard deviation ratio	0.14	0.10	0.19
	Pearson correlation	0.99	0.99	0.98

The sensitivity analysis of input data on output data shows that the durability of the cutting edge is principally dependent on the adhesion of the coatings to the substrate (Table 3, Fig. 5). The change of critical loading, being the measure of coatings’ adhesion, influences the change of cutting edge durability to the highest extent. The other properties like micro-

hardness, coating thickness and grain size have lower impact on the durability changes of the investigated cutting edges. It should be emphasized, however, that from among the other properties the change of grain size has the highest impact on the durability changes of the investigated cutting edges, in particular in the case of coated sialon ceramics; at the same time the durability of the cutting edges is reversely proportional to grain size. The change of microhardness or thickness of the investigated coatings has only slight influence on the durability changes of the investigated cutting edges.

TABLE 3

Results of sensitivity analysis of input data for output data of artificial neural network trained for prediction of PVD and CVD coatings properties deposited onto sialon tool ceramics

Data sets	Statistics	Micro-hardness	Critical load Lc	Grain size	Thickness
Training	Range	4	1	2	3
	Error	2.78	20.30	18.45	5.11
	Ratio	1.33	9.71	8.82	2.44
Validation	Range	4	1	2	3
	Error	3.08	27.12	15.26	4.89
	Ratio	2.49	21.96	12.36	3.96

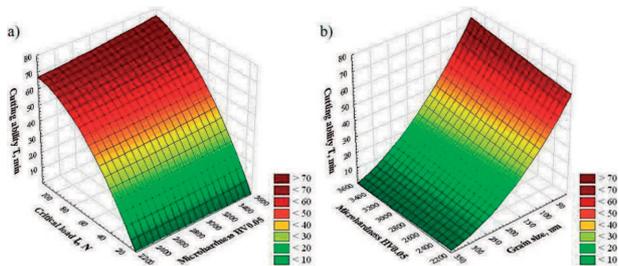


Fig. 5. a) Evaluation of the PVD and CVD coatings critical load and the microhardness influence of tool life T for sialon ceramics tools coated with PVD and CVD coatings determined by artificial neural networks at a fixed coating thickness 3.0 microns and particle size 8.2 nm, b) Evaluation of the PVD and CVD coatings the microhardness and grain size influence of tool life T for sialon ceramics coated with PVD and CVD coatings determined by artificial neural networks at a fixed coating thickness 3.0 microns and critical load 105 N

5. Conclusions

Basing on the carried out research studies the following conclusions can be formulated:

1. It was found that the exploitative durability of the cutting edges from sialon ceramics and sintered carbides covered by gradient and multilayer PVD and CVD coatings depends principally on the adhesion of the coatings to substrate, and to a lower degree on grain size in the coatings, their thickness or hardness changes within 2300÷3500HV.
2. The type of substrate on which the coating is deposited has the influence on the microstructure of the obtained coatings. The PVD coatings of the isomorphic structure with titanium nitride TiN deposited on the substrates from sintered carbides usually demonstrate smaller

grains and higher thickness as compared to their deposition on sialon ceramics. Negatively polarized substrate from sintered carbides brings about the situation where ions which reach the substrate gain higher kinetic energy, the temperature increases to a greater extent than in the case of non-polarized substrate, surface mobility of atoms is rising which leads to the generation of new nuclei and refinement of structure, and furthermore, the growth rate of the coatings on the polarized substrate is higher than on the non-polarized substrate.

3. The PVD coatings demonstrate good adhesion to the substrate from sintered carbides, they are characterized by adhesive-diffusive adhesion mechanism which is conditioned by the diffusive dislocation of chemical elements in the transit zone coating-substrate, which in the case of PVD coatings is effected by the implantation of high-energy ions falling on negatively polarized substrate, and in the case of CVD coatings results in the situation where both the working gas and carbon coming from the substrate are the source of carbon. And good adhesion to sialon ceramics is exhibited by PVD coatings containing AlN phase of the hexagonal structure having covalence bonds of the same type as ceramic substrate.

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