PROPERTIES OF CUTTING INSERTS WITH DIFFERENT PVD COATINGS

**I. MRKVICA[1], J. PETRU[1], V. SLEHA[1], M. NESLUSAN[2]
J. JURKO[3], A. PANDA[4]**
[1]VSB-Technical University of Ostrava
Faculty of Mechanical Engineering, Department of Machining
Assembly and Manufacturing Metrology, Ostrava, Czech Republic,
[2]Žilina University in Zilina, Faculty of Mechanical Engineering
Department of Machining and Manufacturing Technologies
Zilina, Slovakia,
[3]Technical University of Kosice
Faculty of Manufacturing Technologies with seat in Presov
Department of Process Engineering, Presov, Slovakia
[4]Technical University of Kosice
Faculty of Manufacturing Technologies with seat in Presov
Department of Manufactory Process Operation, Presov, Slovakia

DOI: 10.17973/MMSJ.2015_06_201501

e-mail: ivan.mrkvica@vsb.cz

The article evaluates and compares PVD coatings. The theoretical part of the paper informs about principle of PVD coating technology and describes the arc evaporation method used for coating in greater detail. It also deals with coating materials and types and its properties. In the experimental part of the paper, the measuring and testing procedures are described and the test results are listed. Adhesion and layer durability were compared by cutting inserts with different PVD – nanostructure and nanolayer coatings. The tests were carried out by milling of carbon engineering steel 1.1191 (C45). In conclusion the testing results are evaluated on the basis of obtained information.

KEYWORDS
coating, PVD and ARC methods, nanocomposite layers, adhesion, layer durability

1. INTRODUCTION

Protective cutting tool coating together with cutting material, tool geometry and cutting conditions has a significant effect on tool edge durability, which is the sign of successful machining. The main method of cemented carbide tools coating is CVD (Chemical Vapour Deposition, PCVD, MTCVD) method with high process temperatures (1000–1200 °C, 400–600 °C, 700–800 °C). However, PVD (Physical Vapour Deposition) method is used increasingly. It is characterized by lower process temperatures (below 500 °C). This method was originally developed for high-speed steel coating, where tool material structure can be thermally influenced due to high temperatures. Recently, there is a significant development of PVD coating methods and their applications even at the field of cemented carbide tools.

With PVD methods, coatings are produced at reduced pressure (0.1–1.0 Pa) by particle (atoms, cluster of atoms) condensation. These particles are released from particle source (targets) using physical methods such as sputtering (by accelerated Ar ions generated in crossed electromagnetic field) or evaporation (inductively, by low-voltage arc, laser or electron beam) and some methods use even resistance heating [Humar 2008].

Released particles are ionized and react with inert plus reactive gases and after that they are accelerated by negative bias voltage (hundreds of volts) to the surface of substrate. Here these ions create coating, which is thin and homogeneous (usually from 1 to 5 μm.)

Complex vacuum system of all PVD methods is disadvantageous. The same valid for requirement of coated objects movement to guarantee uniform coating deposition over the entire surface and preventing the unwanted shadowing effect. On the other hand, PVD methods allow us to coat sharp edges with radius below 20 μm.

The following text explains the evaporation method, which is currently the most important variant of PVD coating.

2. LOW-VOLTAGE ARC PVD TECHNOLOGY OF COATING WITH ROTARY CATHODES

The coating material is evaporated from electrodes by an arc and simultaneously ionized by it (uncharged atoms become charged – ions). Ionized material (e.g. Ti^{+}, Ti^{2+}) is accelerated to the tool surface by negative bias voltage, which is applied on it. On its way this material ionizes atoms of atmosphere (e.g. Ar, N_2). After reaching a tool surface, charged particles create deposited layer as the result of the surface reactions.

Low-voltage arc parameters are very interesting. Arc burns on the cathode surface at the cathode spot with 10 μm diameter and reaches temperature around 15 000 °C. Under these conditions any electrically conductive material can be evaporated. The targets (evaporated material) have to be positioned closely to the coated objects and ionization level has to be high. This problem can be optimally solved by using rotary electrodes (ARC).

The internal arrangement of the coating chambers with rotary cylindrical electrodes has three possible variants, which differ from each other by an electrode positioning. It is possible to position them centrally (in the middle of a coating chamber) or laterally, for example in access door (LARC system – LAteral Rotating Cathodes). The last variant combines both previous electrode positions (CERC system – CEntral Rotating Cathode) – Fig. 1.

By variable electric current values applied to the electrodes it is possible to control stoichiometry, growth rate and roughness of layers without changing electrode material. Basic coating structures such as mono- (TiN, TiCN) [Cselle 1999, Cselle 2004, Cselle 2005, Fromme 2005, Holubar 2004], multi-, gradient and nanolayers (TiAlN, AlTiN, TiAlCN, CrTiN, AlCrN, TiAlCrN), nanocomposite (TiAlN/SiN, CrAlN/SiN, AlTiCrN/SiN) are prepared in this way.

The multilayers in general slow cracks development and increase layer hardness. Simultaneously the multilayered structure allows us to produce thicker layers than in case of the monolayers.

The gradient or nanogradient layers are systems with continuously changing hard components ratio (e.g. AlN). Higher Al ratio near to the layer surface secure high oxidation resistance while maintaining adequate hardness.

The nanolayers are multilayered systems with each individual layer thickness below 10nm. If these single layers have different physical properties and the interface between them is abrupt enough, then it is possible to find out the optimal layer period, which greatly increases hardness.

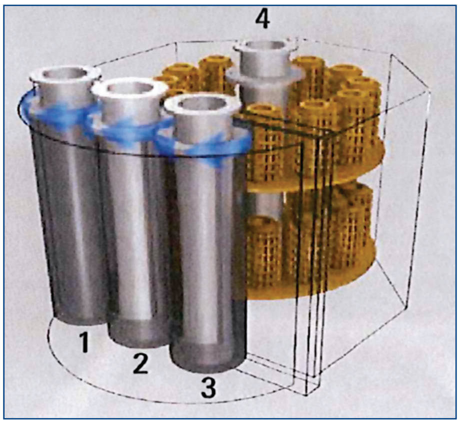

Figure 1. Scheme of PVD coating equipment with centrally and laterally positioned cathodes [Cselle 2011a]

Thanks to their structure, the nanocomposite layers are highly resistant to oxidation and they are thermally stable. Nanocomposites are represented by nc- (Ti1-xAlxN/a-Si$_3$N$_4$) layer. TiAlN is crystalline component and Si$_3$N$_4$ is amorphous matrix. This structure is among the hardest PVD coatings in the commercial sector, its hardness HV values go over 40 GPa. CrAlN based layers are alternatives to TiAlN [Kraus 2007, Peyerl 2010]. CrAlN advantages include good chemical stability at high temperatures and increased adhesion to the substrate.

TripleCoatings$^{3®}$ consist of conventional and nanocomposite coatings. They are deposited in three phases. The best adhesion is achieved by using titanium and/or chrome without using of alloyed targets. Thanks to the similar Young´s moduli the adhesive layer (TiN, CrN, CrTiN) allows a smooth transition between substrate and coating. Because of its low internal stress the middle layer provides a robust core with a good resistance to wear as well as superior hardness (AlTiN, AlTiCrN). The central cathode (position 4 in figure 1) ensures a high deposition rate it means high productivity. The nanocomposite top layer shows an extremely high hardness and an excellent thermal isolation as well as a high resistance against abrasive wear [Cselle 2009].

The "universal" configuration of targets (position 1-Ti, 2 – AlSi, 3 – Cr, 4 – Al/Ti) offers the highest flexibility. More than 30 different coatings can be deposit without cathode exchange [Cselle 2011a]. Current oxide, oxynitride and DLC (Diamond-Like-Carbon) coatings are based on an evolution of the TripleCoatings$^{3®}$ principle [Cselle 2011b, Piska 2014].

Aim of QuadCoatings$^{4®}$ is integration of additional 4th feature e.g. extreme heat isolation with AlON or lubrication with CrCN. Catode configuration for QUADCoatings$^{4®}$ is e.g. Ti-Al-TiSi-Al/Cr, or Ti-Al-Cr-Al/Cr [Cselle 2014]. Comparison of both type of coating is shown in Fig. 2.

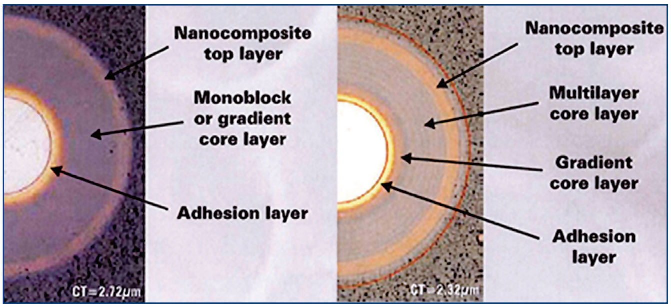

Figure 2. 3rd and 4th coating generations and their structures [Cselle 2014]

3. MEASUREMENT OF ADHESION AND DURABILITY OF DIFFERENT PVD LAYERS

The primary physical properties of layers include hardness, thickness, roughness, adhesion and tribological properties. The most important chemical properties are oxidation resistance, chemical and thermal stability. By experiments were tested three types of coatings applied on the fine grain cemented carbide substrate based on tungsten carbide with low cubic carbide content (TaC and NbC – 1.5 %) and with high bonding phase content (Co – 10.2 %). Substrate hardness was 1310 HV, material density 14,5 g.cm^{-3} and toughness 195 N.mm^{-2}. The tested coatings were applied on square tool inserts with length of cutting edge 12,7 mm – Fig. 3.

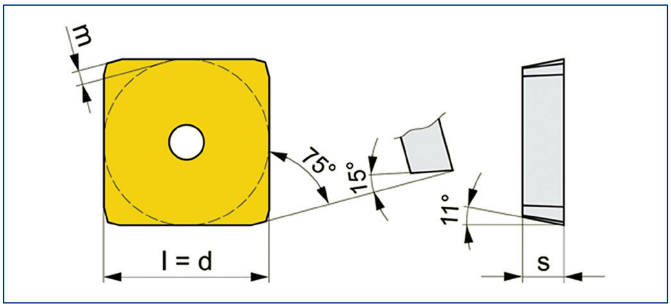

Figure 3. Cutting insert SPKN 1203EDER for experiments [Pramet 2012]

Sample No. 1:
TiN + TiAlSiN nanocomposite + TiN – layer thickness 6,15 µm.

Sample No. 2:
TiN + TiAlN nanolayer + AlTiN, layer thickness 6,65 µm.

Sample No. 3:
TiN + AlTiN nanolayer + TiN – layer thickness 8,75 µm.

3.1 ADHESION

Maximum utilization of protective coating potential is possible only with its good adhesion to the substrate. Scratch-test is the standard method used for testing coating adhesion. The principle is drawing the diamond Rockwell indenter tip across the coated surface under incremental or progressive load. Considering common adhesion values, the load is usually from 20 to120 N. It is also possible to detect acoustic emission of the tip. Upon reaching a critical load, the coating will start to fail and separate from substrate and step increase in the value of acoustic emission will occur.

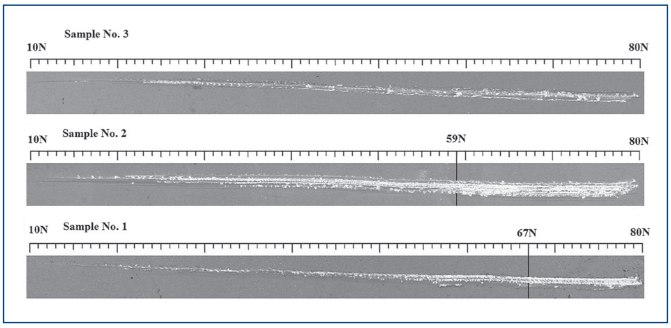

Figure 4. Results of scratch test [Sleha 2013]

Evaluated samples were loaded with linearly increasing force from 10 to 80 N. The chosen criterion for determining critical load is the start of peeling the entire width of scratch. The worst adhesion has sample 2 without upper TiN layer, peeling occurred at critical load of 59 N. TiN is characterized by good adhesion properties and both samples with TiN upper layer have better adhesion. Sample 1 was measured to have a critical load of 67 N. Sample 3 has the best adhesion, peeling the entire width of scratch have not occurred. It is caused by tougher nanolayered structure, which slows and diverts cracks.

3.2 LAYER DURABILITY TEST

Experimental conditions are listed in Tab. 1. Flank wears VB$_B$ = 0,2 mm and VB$_C$ = 0,4 mm [ISO1993] were chosen as a criterion for durability evaluation. The results of experiments are shown in Tab. 2 and Fig. 5–8.

During the initial phase of long-term test, the wear development of all samples was similar. At time around 40 minutes, the flank wear of samples 1 with nanocomposite rapidly increased and the average tool

Machine	Milling machine FCV 63
Cutting tool	Milling cutter 125B09R-W75SP12D, diameter 125 mm, number of teeth = 9, $\kappa_r = 75°$, $\gamma_p = +7°$, $\gamma_f = 0°$
Cutting insert	SPKN 1203EDER – Fig. 3 – l = 12,7 mm, s = 3,18 mm, m = 0,95 mm
Work material	C45, 1.1191, 100 x 100 x 800 mm
Cutting conditions	v_c = 260 m.min^{-1}, f = 0,2 mm, a_p = 2 mm, a_e = 100 mm, with coolant

Table 1. Experimental conditions

Sample	Test	Durability (min)	Average durability (min)	Productivity
1	1	51,0	52,5 ± 1,52	71 %
	2	54,0		
2	1	72,0	68,2 ± 3,82	92 %
	2	64,4		
3	1	75,7	74,3 ± 1,49	100 %
	2	72,8		

Table 2. Average tool durability values

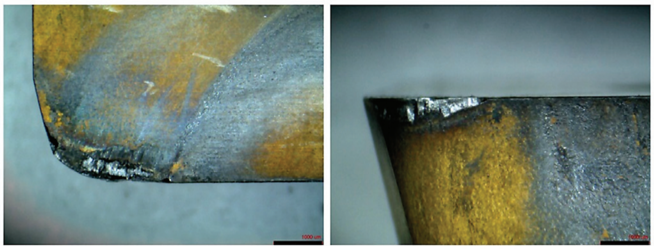

Figure 5. Wear of sample 1 after 60 minutes

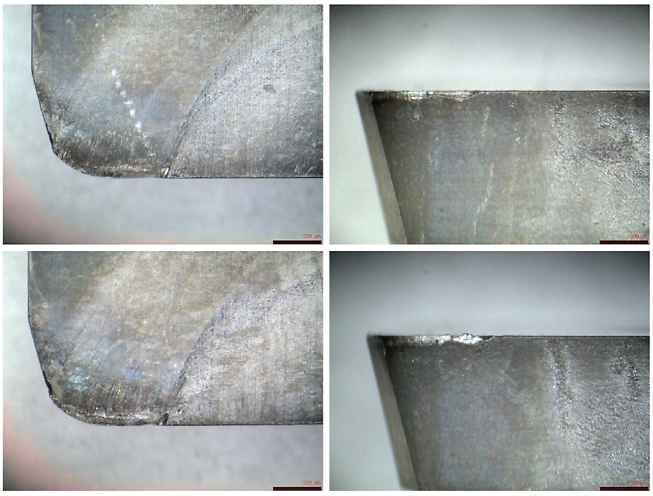

Figure 6. Wear of sample 2 after 60 minutes (up) and after 72 minutes (down)

Figure 7. Wear of sample 3 after 60 minutes (up) and after 78 minutes (down)

durability with this coating is 52,5 minutes. Nanocomposite structure and the lowest thickness are the main reasons of shorter tool life.

Flank wear was chosen as a criterion for durability evaluation. This wear type is characterized by abrasion, which depends on tool material hardness. Samples 2 have upper AlTiN layer containing Al, which increases hardness. But its structure consist from TiAlN nanolayer has lower hardness due to lower Al ratio. The most durable are samples 3 with upper TiN layer and higher Al content in nanolayered structure. Results were also affected by a coating thickness and nanocomposite structure thickness itself.

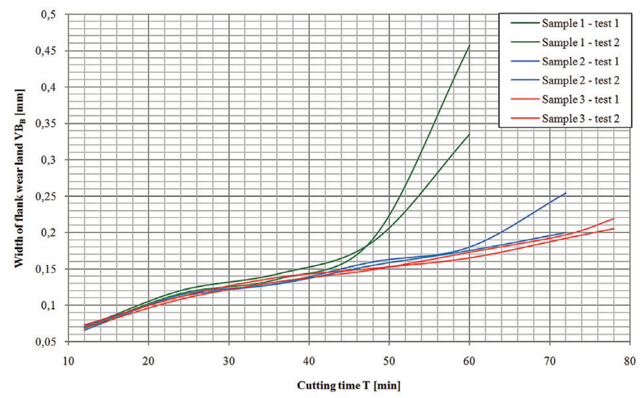

Figure 8. Development of flank wear

4. CONCLUSION

From the previous overview of modern coatings is evident, that the top PVD coating manufacturers are able to produce coatings for any application. In case of cutting tools, performance is affected not only by protective coating, but also by cutting geometry, substrate material and machining parameters, such as cutting conditions.

Aim of the paper was to compare some properties of three different PVD coatings with nanocomposite and nanolayer structure.

- Regarding layer hardness, hardness of the sample 3 was the highest (3 086 ± 76 HV), the second highest sample 2 (2 903 ± 21 HV), and the lowest sample 1 (2 627 ± 96 HV). Structure of nanolayers significantly increase hardness of samples 2 and 3 beside the nanocomposite sample 1. These two nanolayers differ from each other by Al:Ti ratio, whereas according to [Padley 2013], increasing Al ratio in AlTiN layers improves their hardness, but only to Ti:Al = 40:60 %. Higher Al ratio decrease layer hardness. The experiment results correspond to it, sample 3 with higher Al content in nanolayer structure with the ratio Ti:Al = 44,1:55,9 % has higher hardness than sample 2 with the ratio Ti:Al = 54,5:45,5 %. (All samples were measured three times. By chosen load are the results of measurement influenced by substrate and do not give real hardness of coating system. But this load is good enough for mutual comparison of these coatings.)
- Regarding layer thickness, thickness was measured on six spots of cutting insert cross section (in four corners plus in the middle of tool face and opposite surface) to determine coating uniformity. The thickest coating was applied on sample 3 (edges 8,75 μm, planar surfaces 3,45 μm), the second thickest on sample 2 (edges 6,65 μm, planar surfaces 2,75 μm) and the thinnest on sample 1 (edges 6,15 μm, planar surfaces 1,65 μm). Average thickness values on the edges and planar surfaces of tool face differ from average values of opposite surface maximally by 0,1 μm. The ratio between thickness on edges and planar surfaces is lowest on sample 2, so it has the most uniform coating. The second most uniform coating is on sample 3 and the highest ratio and the worse layer uniformity has sample 1. (The most of machining process is realized in area of inserts corner. Layer thickness in this place is important for tool life of cutting insert.)

- Results of adhesion test is listed in Fig. 4 in Chapter 3.1. The best adhesion has shown sample 3 with nanolayer structure AlTiN.
- Regarding long-term test, nanolayer coatings are tougher than nanocomposite layer. By milling long-term test it is possible to achieve better results. Flank wear was chosen as a criterion for durability, abrasion is the predominant mechanism of wear. Surface of sample 2 is formed by AlTiN, which has higher hardness than TiN. On the other hand the hardness of nanolayers TiAlN is – owing to lesser representation of Al in structure – smaller than hardness of nanolayers of sample 3. By this sample is ratio Ti/Al 44,1/55,9 %. Sample 3 has shown the highest hardness of all tested samples. The results were also influenced by thickness of nanolayers and all coating which has this sample the biggest.

ACKNOWLEDGMENT

This article has been done in connection with project Increasing of Professional Skills by Practical Acquirements and Knowledge, reg. no. CZ.1.07/2.4.00/17.0082 supported by Education for Competitiveness Operational Programme financed by Structural Founds of Europe Union and from the means of state budget of the Czech Republic and by project Integrita No.CZ.1.07/2.3.00/20.0037 and Student Grant Competitions SP2015/116 and SP2015/129.

REFERENCES

[Cselle 1999] Cselle, T. New coating for rotated tool (in German). VDI-Z Special Werkzeuge, August 1999, pp. 38-42. ISSN 0931-864X.

[Cselle 2004] Cselle T. With coating technology to increase (in German). Werkstatt und Betrieb, 2004, Vol. 137, No. 5, pp. 84-88. ISSN 0043-2792.

[Cselle 2005] Cselle, T. Inhouse-coating versus pay-coating (in German). Werkstatt und Betrieb, 2005, Vol 138, No. 6, pp. 22-26. ISSN 0043-2792.

[Cselle 2009] Cselle, T. Adapt to use (in German). Werkstatt und Betrieb, 2009, Vol 142, No. 11, pp. 30-34. ISSN 0043-2792.

[Cselle 2011a] Cselle, T. Compendium 2011. Grenchen: Platit AG, 2011.

[Cselle 2011b] Cselle, T., et al. Dedication – Integration – Open Source New Rules in the Coating Industry (and in progressive economics). Werkzeug Technik, 2011, No. 120b, pp. 22-29. ISSN 0997-6981.

[Cselle 2014] Cselle, T. Compendium 2014- Platit AG. URL: http://www.platit.com/sites/default/files/pdf/compendium_ev54b_lowres.pdf (16.4.2015)

[Fromme 2005] Fromme, M., Arndt, M. High-efficiency coats for precise tools (in German), Werkstatt und Betrieb, 2005, Vol 138, No. 6, pp. 20-21. ISSN 0043-2792.

[Holubar 2004] Holubar, P., Jilek, M. and Ruzicka, M. Modern PVD coatings for cutting applications and working (in Czech). MM Prumyslove spektrum, 2004, No. 9, pp. 106–107. ISSN 1212-2573.

[Humar 2008] Humar, A. Cutting tool materials (in Czech). Prague: MM publishing, s. r. o., 2008. ISBN 978-80-254-2250-2.

[ISO 1993] ISO 3685. Tool-life testing with single-point turning tools. Geneve: International Organization for Standardization, 1993.

[Kraus 2007] Kraus, J. PVD-coating for separate of hard oxide coats (in German). MM Industriemagazin-Maschinenmarkt, 2007, No. 1/2, pp. 32. ISSN 0341-5775.

[Paldey 2003] Padley, S., Deevi, S.C. Single layer and multilayer wear resistant coatings of (Ti,Al)N: a review. Materials Science and Engineering: A, 2003, No. 342, pp. 58-79. ISSN 0921-5093.

[Peyerl 2010] Peyerl, G. PVD-coatings on AlCrN base increase tool productivity (in German). MM Industriemagazin-Maschinenmarkt, 2010, No. 31/32, pp. 37. ISSN 0341-5775.

[Piska 2014] Piska, M. Trends in PVD and CVD coating (in Czech). MM Prumyslove spektrum, 2014, No. 11 – supplement, pp. VIII-IX. ISSN 1212-2573.

[Pramet 2014] Pramet Tools. Pramet Milling 2014. URL: http://www.pramet.com/cz/produkty/frezovani/vymenitelne-britove-desticky.html (16. 4. 2015)

[Sleha 2013] Sleha, V. Application area of PVD Coatings by cutting tools from cemented carbide. (Bachelor thesis in Czech). Ostrava: VSB – Technical university of Ostrava, Faculty of Mechanical Engineering, Department of Working and Assembly, 2013.

CONTACTS

Assoc. Prof. Ivan Mrkvica, Ph.D., MSc.
VSB-Technical University of Ostrava
Faculty of Mechanical Engineering
Department of Machining, Assembly and Manufacturing Metrology
17. listopadu 15/2172, 708 33 Ostrava, Czech Republic
tel.: +420 597 324 451, e-mail: ivan.mrkvica@vsb.cz
www.vsb.cz