ELSEVIER
SciVerse ScienceDirect
Procedia CIRP 9 (2013) 8 – 12
www.elsevier.com/locate/procedia

2nd CIRP Global Web Conference

Development of wear-resistant complex for high-speed steel tool when using process of combined cathodic vacuum arc deposition

Vereschaka A. A.[a*], Volosova M. A.[a], Grigoriev S. N.[a], Vereschaka A. S.[a]

[a] *Moscow State University of Technology (MSUT "STANKIN"), Vadkovsky per. 3a, 127055, Moscow, Russia.*
* Corresponding author. Tel.: +7 499 972-95-21;.*E-mail address*: ecotech@rambler.ru.

Abstract

The paper studies the technique for increasing efficiency of high-speed steel tools by forming wear-resistant complexes when using processes of combined cathodic vacuum arc deposition with filtration vapour ion flow. Based on analysis of the causes of premature destruction of standard coatings on high-speed steel tools, provisions were designed to increase the effectiveness of wear-resistant coatings by increasing their operating life till partial or complete destruction. For that purposes, architecture of wear-resistant complex was developed for formation on substrates of high-speed steel. Wear-resistant complex includes thermally stabilizing layer and three-element multi-layered composition nano-dispersion coating, and it can be formed by using the combined process of cathodic vacuum arc deposition with filtration vapour ion flow. The paper presents data on the optimization of the conditions for formation of the wear-resistant complex elements that provide a significant increase in tool life of high-speed steel tool both with continuous and interrupted cutting.

Selection and peer-review under responsibility of International Scientific Committee of the 2nd CIRP Global Web Conference in the person of the Conference Chair Dr. Sotiris Makris

Keywords: wear-resistant complex; combined processes of filtered cathodic vacuum deposition; thermally stabilizing layer; nano-dimensional multi-layered composite coating; tool life.

1. Introduction

Based on the analysis of the causes for intense destruction of coatings on contact areas of high-speed steel tools and on the results of studies on the kinetics and mechanisms of wear of a tool with various coatings [1,2,3]. It was found out that, despite significant decrease of wear rate in the case of coatings of contact areas, their effectiveness remains significantly lower than expected [4,5,6,9,10,11]. In particular, for various types of high-speed steel tool (lathe tools, drills, shaping cutters, worm hob and end mills, taps), wear resistance of TiN coating is 0.5-10% of the tool life period [1,2,3,4].

The main causes of destruction of coatings on substrates of high-speed steel are related to: - high-temperature creep and propensity of tool's cutting part to elastoplastic deflections and loss of dimensional stability; - insufficient strength of adhesive bond between coating materials and tool; - defects of coating. Besides, premature destruction of coating can be caused by critical stress at the border of "coating-tool material" section, which arises under thermomechanical loading of tool contact areas. These stresses are largely dependent on the difference in thermal, physical and mechanical properties of coating material and tool, microstresses in surface layers of tool material after full thermal processing and grinding [12,13,14].

Thus, the development of methods of increasing durability of coatings on substrates of high-speed steel represents an important scientific problem in developing high-speed steel tools with wear-resistant coatings.

2. Methodology

Methods to improve efficiency of wear-resistant coatings on contact areas of high-speed steel (HSS) tools were developed based on a detailed study of contact processes, thermal conditions of tool's cutting part and tool wear mechanisms for the various machining operations of cutting (turning, drilling,

Selection and peer-review under responsibility of International Scientific Committee of the 2nd CIRP Global Web Conference in the person of the Conference Chair Dr. Sotiris Makris
doi:10.1016/j.procir.2013.06.159

milling, broaching).

According to the adopted provision, increase in durability of coatings on substrates of HSS can be achieved by increasing plastic strength and stiffness of HSS tool cutting wedge by forming wear-resistant complex (WRC) (Fig. 1), consisting of thermally stabilizing layer (TSL), adhesive sublayer (ASL), intermediate layer (IML) and wear-resistant layer (WRL).

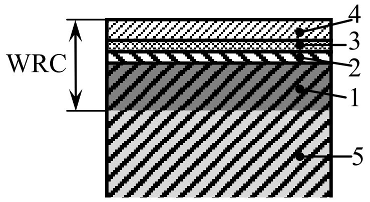

Fig.1. Layout of WRC formed on working surfaces of a high-speed steel tool: 1 - thermally stabilizing layer (TSL); 2 - adhesive sublayer (ASL); 3- intermediate layer (IML); 4 – wear-resistant layer (WRL); 5 – high-speed steel substrate (HSS).

Each of the WRC elements performs strictly regulated functions:

- thermally stabilizing layer (TSL) supports increase of plastic strength and stiffness of cutting wedge of HSS tool;
- adhesive sublayer (ASL) enhances adhesion strength between WRC and HSS substrate;
- intermediate layer (IML) provides sufficient adhesion strength of "WRL-IML-ASL" systems;
- wear-resistant layer (WRL) performs basic function to increase wear resistance of HSS cutting tool.

The subject of research was represented by square inserts with dimensions 18 x 18 x 6 mm of HSS grade R6M5 (6% W, 5% Mo) with r = 1,2 mm, subjected to standard thermal processing, and these inserts were used to equip lathe tools and face-milling cutters in testing to assess tool wear-resistance.

Combined cathodic vacuum arc processing (CCVAP) of a HSS tools was conducted within one technological cycle in multifunction installation (Fig. 2), equipped with a device for generation of gas and metal-gas plasma of vacuum arc discharge [6,7,8,9] and a device for filtration of vapour ion flow.

Method of formation of the WRC on a HSS substrates, when using the CCVAP, is as follows (see Fig. 2). The target 1 of Ti, used as cathode of arc discharge, vaporizes as cathode spot of a vacuum arc in vacuum space of the chamber 5, and the filtering cathode system 3 (Al) is disabled. The special screen 4, located between the target 1 and the anode 2, divides the chamber 4 into two areas, filled with metal-gas plasma (to the left of the screen) and gas plasma (right). The screen 4 is impenetrable to microdroplets, neutral atoms 5 and metal ions 6 emitted by cathode spots from the surface of the titanium target 1. The screen 4 is penetrated only by electrons that on their way to the anode heat samples of the tool 9 when positive potential is applied to them, and they form gas plasma. When negative potential is applied to the tool 9, TSL of the WRC is formed by ion nitriding of the substrate surface.

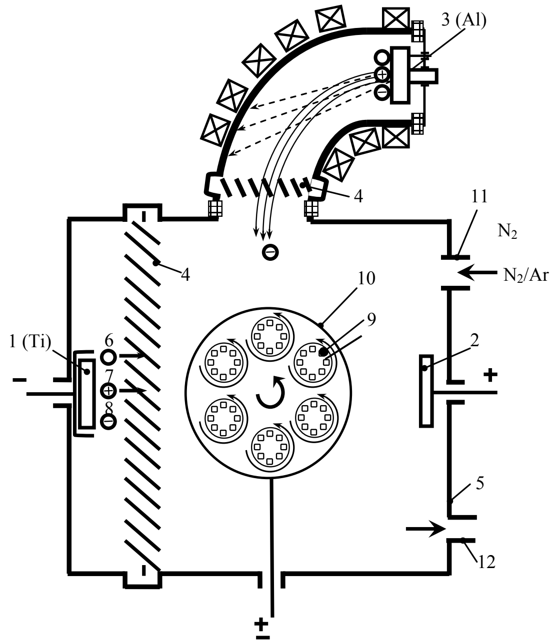

Fig.2. Principle layout of multi-functional cathodic vacuum arc plant: 1- titanium target (cathode); 2- anode; 3 - aluminum target (cathode) with filtration of droplet component; 4 - special screen; 5 - vacuum chamber of the installation; 6,7,8- microdroplets, metal ions and electrons; 9 – tool samples carrying planetary motion in the chamber; 10 – turning table with mounted tool samples, 11 - gas inlet valve, 12 - vacuum pumping system.

During the nitriding, the process parameters were varied as follows: temperature was 420 ... 510°C; concentration of N_2 nitrogen in gas mixture with argon was 10 ... 100% at.; nitriding time was 10 ... 70 min. Due to the fact that the pressure range, in which vacuum arc discharge exists, is quite narrow, in all cases, nitriding was carried out at pressure of $9.75 \cdot 10^{-1}$ Pa. After the process of formation of TSL, the screen 4 was displaced, and voltage was applied to cathode systems 1 (Ti) and 3 (Al), and after that, the synthesis of coating layers was conducted. During the experimental testing, multi-layered composite coating Ti-TiN-TiAlN was used as an example of wear-resistant coating, which was formed using titanium (evaporator 1) and aluminum (filter evaporator 3) cathodes. When applying coating, only deposition time was varied within the period from 40 till 100 minutes. In all cases, other process parameters remained constant: temperature was 450-470°C;

reference voltage was 120V, current arc on the cathode was 75-90A (Ti) and 100-120 A (Al), respectively; pressure in the vacuum chamber was $2.6 \cdot 10^{-1}$ Pa; ion current density was 0.5 A/mm^2.

The following parameters of WRC were tested: thickness ("Calotest" method), adhesive bond strength ("Scratchtest" method, "CSEM Revetest" device), microhardness (POLYVAR microscope, equipped with MICRO-DUROMAT 4000 attachment to measure microhardness). Study of crystal-chemical properties of the WRC was carried out using JSM-6700F scanning electron microscope (SEM) with (EMF) JED-2300F attachment for spectral analysis, manufactured by the company "Jeol".

Phase composition and structure of thermally stabilizing (nitrided) layer was studied by the X-ray structure analysis on DRON-4, equipped with computer control and spectrum recording. Symmetrical survey of samples on reflection was performed with use of X-ray tubes with copper and cobalt radiation. This allowed estimating (on average) the phase composition at different depths from the surface (up to ~ 7 and ~ 2 μm, respectively). In some cases, to determine the phase composition of the thin surface layer of up to 0.5 μm, the method of grazing beam (CuKα radiation) was used with a constant entry angle (α = 5°), the spectrum processing was carried out with the help of special programs.

Certification testing of the tool equipped with HSS inserts with WRS, was carried out at uninterrupted cutting (turning) on a machine tool of 16K20 model, with variable-speed drive of main motion and interrupted cutting (symmetric face milling) on a vertical milling machine tool of BM127 model. To eliminate the effect of radial beats of cutter teeth on tool wear, testing was carried out by milling cutter with one tooth.

At turning and milling, 45 (HB 200) steel in the state of delivery was used as the material for machining. Testing was carried out with the following cutting parameters:
at turning: v = 82 m/min, f = 0.2 mm/rev, a_p = 1.5 mm;
at symmetric face milling: v = 89 m/min, f_z = 0.15 mm/tooth, a_p = 1.5 mm, milling width B= 45 mm. Cutting time till tool change was T = 60 min. Tool failure criterion was flank wear land of HSS inserts VB = 0.45-0.5 mm.

At performance test, flank wear land VB_b of HSS inserts was measured by BMI-1C instrumental microscope. Experimental studies were carried out at 3-5 times the duplication, which provided sufficient reliability of the results.

Optimization of modes for CCVAP of samples was carried out by means of mathematical modeling. To develop mathematical relations establishing connection between time of nitriding (τ_N), temperature of nitriding (Θ_N), nitrogen percentage in gas mixture with argon for nitriding (K_N), time of deposition of coating (τ_C) and their influence on wear of cutting inserts at longitudinal turning and face milling, the exponential-power mathematical model was used in the form as follows:

$$\mathrm{VB_b} = c\, \Theta_N^{a_1} K_N^{a_2} \tau_N^{a_3} \tau_C^{a_4} \exp[b_1\Theta_N + b_2 K_N + b_3 \tau_N + b_4 \tau_C] \quad (1)$$

After finding with a program of statistical processing of the experimental data the parameters of mathematical model (c, a_1 ... a_N and b_1 ... bn) with the help of the "MODEL UNI" software to process experimental data, the function of $VB_b = f(\Theta_N, K_N, \tau_N, \tau_C)$ was differentiated in partial derivatives, and first derivatives were equated to zero, resulting in required optimum modes for these vacuum-plasma processing.

4. Results and discussion

Structure and properties of thermally stabilizing layer (TSL). The studies conducted have shown that the composition of gas environment has a strong influence on the structure of TSL formed at ion nitriding of HSS grade R6M5 in gas plasma of vacuum arc discharge. Table 1 shows the X-ray structure analysis of TSL (nitrided) formed at using gas mixtures containing different amounts of N_2 and Ar.

Table 1. Phase composition of TSL under different combinations of gas environment (Temperature of nitriding at 450°C, when time of nitriding lasts 1 hour)

Phase	Volume fraction (%) in a layer		
	100% N_2	40% N_2/60% Ar	10% N_2/90% Ar
Surveying with CuKα-radiation by grazing beam			
Fe_2N	83.7	-	-
Mo_2N	5.5	-	-
$Fe_3(W,Mo)_3(C,N)$	6.8	-	-
Fe_α (C,N)	4.0	-	-
Surveying with CuKα-radiation			
Fe_2N	-	-	-
Mo_2N	-	1.4	1.4
$Fe_3(W,Mo)_3(C,N)$	-	5.6	5.5
Fe_α (C,N)	-	93.0	93.1
Surveying with CoKα-radiation			
Fe_2N	22.7	-	-
Mo_2N	3.4	1.0	1.0
$Fe_3(W,Mo)_3(C,N)$	4.2	4.6	4.5
Fe_α (C,N)	69.8	4.6	4.5

The results obtained point out that surface layer of HSS sample inserts, nitrided at 100% N_2, contains ε-phase of $(Fe,Me)_2N$ type, nitrides of alloying elements Mo_2N (possibly, also W_2N), carbides (or carbonitrides) of type $Fe_3(W,Mo)_3(C, N)$, present in HSS steel as redundant, and α-phase that represents a solid solution of *C* and *N* in Fe_α (martensite).

Evaluation of the phase of TS-layer under nitriding with pure nitrogen by survey with grazing beam method allowed finding out that at depth of up to ~ 1 μm, substantially continuous nitride layer of ε-phase had been formed. When using in nitriding a gas mixture N_2/Ar in ratio of 40-60% N_2/60-40Ar results in blocking ε-phase in surface layer, and the amount of molybdenum nitrides Mo_2N decreases from ~ 5.6-5.5% (at a depth of ~ 2 μm) to 1% (to a depth of ~ 7 μm).

The results of studies have found out a sufficiently strong influence of composition of gas mixture N_2/Ar, temperature and time of nitriding on thickness and maximum microhardness of TSL. It has been found out that increase in the percentage of nitrogen in gas mixture with argon increases the surface hardness of the nitrided layer, but decreases thickness of the layers formed.

Structure and properties of multi-layered composite coating as a part of WRC. The results of studies have found out that multi-layered composite wear-resistant coating Ti-TiN-TiAlN, developed for WRC, has a nano-dimensional layered structure with an average grain size of 10-15 nm and thickness of sublayers of each element (TSL, ASL, IML, WRL) of 20 - 25 nm, has high adhesion strength to TS-layer, high hardness, up to 3,2 GPa, and essentially free of surface droplets, which are dangerous defect of coating.

Wearresistance of a HSS tools with WRC. The studies conducted have shown that the parameters with the decisive effect on the working efficiency of the tool after the CCVAP are as follows: temperature (Θ_N) and duration of nitriding (τ_N), percentage of nitrogen in gas mixture with argon (K_N) and duration of subsequent application of wear-resistant coating (τ_C).

Fig. 3 show the combined effect of the parameters of CCVAP on the wear rate of the tool in longitudinal turning, from which it follows that the tool wear as a function of the parameters of CCVAP has a local extremum in all cases.

Following the processing of the experimental data, the models were developed to present dependence of tool flank wear land on the parameters of CCVAP, which have the form as follows:

for longitudinal turning:

$$VB_b = \frac{2,74 \exp[0,0032\,\Theta_N + 1,73K_N + 1,075\tau_N + 0,82\tau_C]}{\Theta_N^{1,6}\,K_N^{1,04}\tau_N^{0,72}\tau_C^{0,82}} \quad (2)$$

for face milling:

$$VB_b = \frac{0,38 \exp[0,003\,\Theta_N + 4,4K_N + 2,21\tau_N + 1,3\tau_C]}{\Theta_N^{1,38}\,K_N^{1,32}\tau_N^{0,73}\tau_C^{0,9}} \quad (3)$$

Following these calculations, values of the parameters of CCVAP to ensure minimum wear rate of a tool in turning and milling were found.

Metallographic studies have found that WRC, which is formed at the combined cathodic vacuum arc processing and which ensures minimum tool wear rate, meets the following characteristics:

• in continuous turning: effective thickness of TSL h_{TSL} = 50-55 μm with microhardness of 11.9...12.1 kN/mm^2 with thickness of coating Ti-TiN-TiAlN h_C = 6 μm (h_{ASL}=0,5 μm; h_{IML}=1,5 μm; h_{WRL}=4,0 μm)

• in milling: effective thickness of TSL h_N = 30-35 μm with microhardness of 10.5...10.7 kN/mm^2 with thickness of coating Ti-TiN-TiAlN h_C = 4 μm (h_{ASL}=0,5 μm; h_{IML}=1,0 μm; h_{WRL}=2,5 μm)

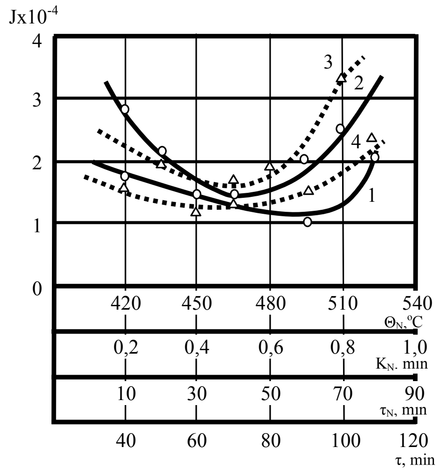

Fig.3. Influence of the CCVAP parameters on wear rate of the major flank face of a HSS tool with WRC (***J***) at longitudinal turning:
1 - temperature of nitriding (Q_N); 2 - duration of nitriding (τ_N); 3 - content of nitrogen in mixture of N/Ar (K_N); 4 - duration of deposition of coating (τ_P).

For control of the developed positions researches of tool life of twist drills Ø =6,8 mm made of HSS became conducted at dry machining of steel 45 (HB 200) with v=35 m/mines; f=0,1 mm/about and depth of drilling l_d=30 mm. Used a uncoated drills, drills with standard coatings and drills with the developed wearresistance complexes which have been formed at various parameters values of CCVAP. Results of researches are presented on fig. 4.

The analysis of the received data allows to notice that drills with the wearresistance complexes received at an optimum parity of CCVAP parameters, more than in 10 times have exceeded tool life of uncoated drills and in 4 times have exceeded tool life of drills with standard coatings. The received result convincingly enough confirms the developed positions about increase of efficiency of the tool made of HSS by formation of wearresistance complexes for one of the most heat-stressed operations of cutting which drilling concerns.

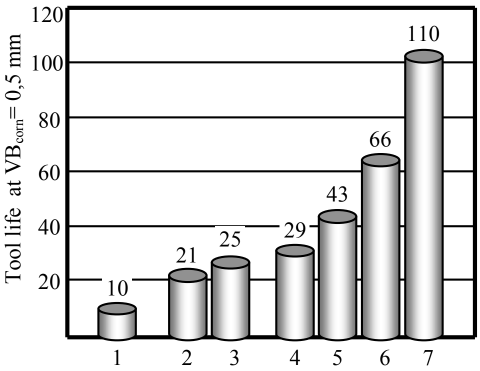

Fig.4. Tool life test for twist drills Ø =6,8 мм made of HSS with various types of WRC and coatings :
1-uncoated; 2 – TiCN;3 – TiN; 4 - N-Ti-TiN-TiCN; 5 – N-Cr-TiCrN; 6- N-Ti-TiN; 7- N-Ti-TiN-TiAlN.

Conclusion

The paper has developed the provisions to increase the effectiveness of wear-resistant coatings on substrates of high-speed steel by increasing their lifetime till partial or complete destruction. To ensure that provisions, the principal layout of WRC deposited on substrates of high-speed steel, including TSL and multi-layered composite nano-dispersed coating was designed, and the technology of its producing on the basis of combined processes of filtered cathodic vacuum arc deposition was developed. The presented technique allows forming WRC on HSS tools in one technological cycle in one vacuum-arc-PVD installation.

Dependence of the phase composition of TSL of WRC on the composition of nitrogen-argon gas environments was found out, and their optimal ratio was determined to exclude formation of high-nitrogen ε-phase, dramatically impairing adhesion strength of WRC and HSS substrate. The optimal ratio of N_2/Ar was found out, providing the minimum wear rate of the cutting tool with wear-resistant complex in turning and milling, and that ratio is 60% N_2/40% Ar for turning operations and 30% N_2/70% Ar for face milling operations, respectively.

Dependence of the performance of high-speed steel tool on the time of formation of TSL, temperature of nitriding, concentration of nitrogen in gas mixture of N_2/Ari, and duration of deposition of coating.

High performance of HSS tools with developed WRC is determined by increase of resistance of tool's cutting wedge to thermo-plastic deformation, and that allows extending the operating life of coating without destruction and all its positive effects like reduced friction and adhesion with respect to the workpiece material, the power of frictional source of heat, etc.

References

[1] Vereschaka, A.S. 1993. Efficiency of the cutting tool with wear resistant coating.Mashinostroenie, Moscow, 336 p.
[2] Vereschaka, A.S. and S.N. Grigoriev. 1990. "Methods of increase of the cutting tools efficiency by complex superficial processing". In: Progressive cutting tools. Technological center of Latvian science Academy, Riga, 137-149.
[3] Grigoriev S.N. 2000. Technology and equipment for complex ion-plasma treatment of the cutting tools. STIN. - № 12, p. 12-16.
[4] Alami J, Persson P.O.A., Music D, Gudmundsson J.T, Bohlmark J ,Helmersson U (2005) On-assisted Physical Vapor Deposition for Enhanced Film Properties on Nonflat Surfaces. Journal of Vacuum Scienceand Technology A Vacuum Surfaces and Films 23(2):278–280.
[5] Biermann D. (2007) Influence of the Coating on the Maximum Width of Flank Wear Land by Turning the Austenitic-ferritic Steel X2CrNiMoN 22-5-3. Proceedings of the 6th International Conference THE Coatings, 97–106.
[6] Lierat F., Vereschaka A. 1999."Entwicklungsstand und - trends der Hartstoffbeschichtung. Tagungsband Magdeburger Produktionstechisches Kolloquium MPK'99. Die Wissensintensive Production, ISBN 3-00 - 004180-x) .7.
[7] Sablev L.P., Andreev A.A., Grigoriev S.N., Metel A.S. US Patent №5,503,725, Europatent №0583473, DE Patent № 69227313T2.
[8] Lierat F. Vereschaka A.S., Pankov A., Lapin V. DE Patent 19733517 A1, C23 C 30/00.
[9] Gorovoy A.P., Fegorov S.V. Volosova M.A. 2001. Influence of plasma nitriding process two-stage vacuum-arc discharge on the structure of the surface layer of high-speed steel / / The interaction of ions with the surface: Proceedings of the XV International Conference. T.2. M.: MAI, pp. 318 – 320.
[10] Lierat F., Vereschaka A. 1998. The main trends of Vacuum-ARC technology synthesis of multi-layered coatings for cutting tool perfection. IX Internationales Productionstechnisches kolloquium PTK-98 Berlin, , pp.211-225.
[11] Faga M.G., Gautier G., Calzavarini R., Perucca M., Boot E.A., Cartasegna F., Settineri L. (2007) AlSiTiN an composite Coatings Developed Via Arc Cathodic PVD: Evaluation of Wear Resistance Via Tribological Analysis and High Speed Machining Operations. Wear 263(7–12):1306–1314.
[12] Grigoriev S.N., Vereschaka A.A., Vereschaka, A.S., Kutin A.A. 2012. Cutting tools made of layered composite ceramics with nano-scale multilayered coatings. Procedia CIRP 1 (2012), pp.318 – 323.
[13] A.S. Vereshchaka, B. Karpuschewski, L. Dubner. Development of the method of obtaining nanostructured functional coatings. Proceedings of the Intern. Scient. Conf. "Production. Technology". V.1. (2008), p. 62.
[14] K.D. Bouzakis, N. Michailidis, G. Skordaris, E. Bouzakis, D. Biermann, R. M'Saoubi. Cutting with coated tools: Coating technologies, characterization methods and performance optimization. CIRP Annals - Manufacturing Technology 61 (2012) 703–723.