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Investigation of thin layers deposited by two PVD techniques on high speed steel produced by powder metallurgy

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ABSTRACT

This study was intended to investigate the properties and cutting performance with thin layers applied by two PVD techniques. PVD techniques ARC and LARC were used for the deposition of thin coatings onto cutting tools prepared by powder metallurgy. Advanced types of layers – monolayer AlTiCrN and nanocomposite type of nc-AlTiN/Si_3N_4 layer – were analyzed by standard techniques for surface status and quality assessment – roughness, hardness, layer thickness, chemical composition by GDOES, tribological properties at room and elevated temperature. Durability testing of the cutting tools was carried out according to the standard ISO 3685-1999. The nanocomposite nc-AlTiN/Si_3N_4 layer achieved lower roughness when compared to monolayer AlTiCrN which leads to the achievement of higher hardness and better layer quality. The HV0.5 hardness values were ~26 GPa. The results showed a 2–3-times longer durability of the cutting tools in comparison with equivalent uncoated PM and traditional materials. The deposited coatings contributed to the improvement of their durability.

1. Introduction

Thin films of transition metal nitrides have been widely used in many engineering applications especially due to their high hardness, chemical inertness and excellent wear resistance. Among them, the properties and the applications of TiN coatings have been studied extensively. The main disadvantage of TiN is its limited oxidation resistance (approximately 450–500 °C). The addition of other elements such as Al, Cr, Si, etc. increases the oxidation resistance of TiN [1,2]. Recently, from the perspective of environmental conservation, dry machining without the use of cutting fluids has been developed and also cutting speeds have been increased to improve cutting efficiency, causing increased temperatures of the cutting edge [3]. TiAlN coatings have been developed for engineering applications as an alternative to TiN since 1986 [4]. Accordingly, materials that can replace TiAlN are required. In the attempt of adding Cr, research shows that a slight addition of Cr to AlTiN results in excellent cutting performance in the cutting of hardened steels [5]. The relationship between the microstructure and properties of nanocrystalline coatings or thin film nanocomposites, which are based on nitrides of transition metals, is the main topic of many studies [6]. This is also true for chromium nitride coatings, which additionally contain aluminium and silicon. The Cr–Al–N and Cr–Al–Si–N coatings are beneficially used in special industrial applications, e.g. for the punching of perforated sheets [7] as superelastic coatings for high end spindle bearings [8] or as thermal barriers redirecting the heat from the cutting tool into the chip [9].

Production improvement of the engineering industry is influenced by increasing requirements on quality, functionality and durability of cutting tools. The cutting tools must be made of material harder than the material which is to be cut, and the tool must be able to withstand the heat generated in the metal-cutting process. To produce quality parts, a cutting tool must have three characteristics: hardness and strength at high temperatures, toughness and wear resistance. So development in the area of cutting tools is focused upon tool surface modification by advanced PVD technologies that are continually improved, and they are generally environmentally friendly because they do not need to use harmful chemical agents and gases. This fact stems from the principle of physical evaporation process of the material, which is a basis of the final coating.

The unique advantage of advanced coatings of [Ti, $Al_{1-x}Cr_x$]N and nc-AlTiN/Si_3N_4 types is in their exceptional properties, such as: very high oxidation resistance (above 900 °C) with a high hardness of 38–50 GPa [10–14]. They are thermodynamically stable materials, also from the point of view of granularity – grain growth does not occur even at temperatures above 1000 °C. Grain boundaries act as an effective barrier against defect propagation, and high hardness of these materials is determined in this manner.

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Table 1
Commercial chemical composition of PM high speed steels used [25].

Material	Chemical composition (wt%)							
	C	Cr	Mo	W	V	Co	Si	Mn
VA 30	1.30	3.99	4.81	6.17	3.1	8.20	0.64	0.24
S 390	1.65	4.70	1.88	10.13	4.75	7.77	0.61	0.29

Layers (Ti, Al, Si)N, that form (Ti,Al)N nanocrystals in a size about 5 nm, are distributed in amorphous Si_3N_4 matrix [15]. Other positive features are the low coefficient of friction, high thermal and low chemical affinity to the machined material [16–19]. Application of these coatings is realizable thanks to new PVD technologies using lateral rotating electrodes, called LARC® technology (lateral rotating arc-cathodes) [20,21]. The techniques described ensure high wear resistance under high-speed machining conditions when cutting tool oxidation wear is dominant. The major cause of the high wear resistance of TiAlN and nc-$(Ti_{1-x}Al_x)N$/a-Si_3N_4 coatings during high-speed machining is the formation of the protective alumina films on the cutting tool surface [22]. Evaluation of some properties of the system thin layer–substrate needs specific methods and procedures. The most important mechanical properties from the point of view of this application are hardness and the adhesion of thin coating to substrate [23].

Described in this contribution are the above-mentioned layers deposited on specimens from high speed steels, which were tested by selected methods. These methods are in correlation, and together they can give us information about the quality of applied layers.

2. Experimental procedure

Coatings were deposited by means of a physical vapor deposition (PVD) process. Two techniques for coating were used–the classic ARC method with its four planar electrodes located in the corners of the chamber (Cr, AlTi, Cr, AlTi) on "PLATIT 1000" equipment [24] and progressive LARC® technology (lateral rotating electrodes) for coating deposition nc-AlTiN/Si_3N_4 (*designated as nACo*). An improvement of this modern technology is based on the rotating cathodes and their lateral position. The deposition unit was equipped with the lateral arc rotating cathodes (LARC) system [24] with two laterally rotating cathodes. During the process, evaporated metals and metal alloys enter the plasma state to combine with the ionized process gas (nitrogen) and eventually condense on the substrate surface, as part of ceramic compounds. Amorphous and micro-nanocrystalline structures and layers are developed with optimized thermodynamic and kinetic conditions. Spinoidal decomposition allows building TiN nanocrystalline structures dispersed in a Si_3N_4 amorphous matrix, with a typical crystallite size of about 10 nm [20].

Two high speed steels grades of S 390 Microclean (*signed S 390*) and Vanadis 30 – Super Clean (*signed VA 30*) [25] produced by powder metallurgy (PM) were used as substrates. The selected material grades belong to the group of high performance high speed steels alloyed with cobalt, with excellent abrasion resistance, good toughness and machinability. Their commercial chemical composition is listed in Table 1. Two types of steel with cobalt contents of 8% were used for technical reasons. Samples from these materials were coated by PVD technology with composite thin layers of the thickness to 2.5 μm. The coated specimens, and for comparison non-coated ones as well, were subjected to selected testing analyses.

The roughness of the coating surfaces was analyzed by atomic force microscopy (AFM, Dimension icon by Veeco Instruments) from the statistically significant compilations, the so-called flat sectors of the coated surface samples. The dimensions of the particles were also defined by the linear method on the surface of the layers and documented in 2D and 3D modes.

Hardness was measured by the microhardness tester LECO LM 700 AT with a load of 0.5 N, and the results were statistically treated using 20 values from each sample. The coated and, for comparison, also the non-coated specimens were subjected to the selected testing analyses.

Pin-on-disc tests were used to evaluate wear resistance of the deposited coating. Fundamental information about behavior of the thin layer – substrate system was obtained by analysis of the trace after the pin movement and the extent of the track deterioration. The tests were realized at room and elevated temperature (400 °C) with a constant load of 5 N on the pin (WC ball was used as a pin) with a sliding speed of 4 cm s^{-1}. The result was a graphical record of the coefficient of the friction course during ca 10,000 cycles.

Another suitable method to evaluate the layers and wear resistance is the Calotest. A rotating steel ball in a diameter of ca 25 mm forms a trace on the specimen surface. The trace called calotte allows calculating the layer thickness and also to monitor relevant changes and failure of the layer at transitions between layers up to the substrate. A more detailed method description is in [26].

The GDOES method (glow discharge optical emission spectroscopy, GDS-750) was used for qualitative and quantitative determination of metallic and non-metallic elements through a cross section of applied layers. Its output is tabular values and vertical concentration profile allowing a graphical record of the concentration changes of selected elements up to a depth of 0.1 mm of the investigated material. From the concentration profile it is possible to approximately deduct the layer thickness as well. Conversion accuracy of the measurement time axis to the concentration profile axis is given by determination of the exact removal rate of individual calibration standards. Because the measured structures are heterogeneous and multi-component, mistakes in these recalculations are to be expected. There is no universal way for the elimination of these inaccuracies and it is necessary to proceed from one case to the next [27]. Therefore it is necessary to correct the increased or lowered signal intensity according to the principle of respective calibration. Nearby emission lines have a cardinal importance in cases of quantitative measurement of chemical composition. Selection of individual wavelengths for analytical purposes is subjected to some further steps, which are listed in the methods described in [28].

Thin films are usually applied to the cutting plate and also tools for machining. The tests were realized according to the standard STN ISO 3685-1999. "Durability testing of turning tools with one cutting edge". A durability test of the cutting tools with applied coatings was carried out under pilot conditions by the so-called long-time cutting test. Cutting blades of the type SPUN 120504 were prepared for long-term durability testing according to the standard ISO 3685-1999. The steel (ISO 683/1-87) was used as machining material. This steel corresponds to the 41 2050.1 steel (according to STN 41 2050) with tensile strength $R_m \leq 700$ MPa [29].

The cutting process is focused upon the area of cutting tool edge contact with machined material in the cutting zone. The properties of machined surface in the cutting zone depend on