Influence of Thickness of Multilayer Composite Nano-structured Coatings on Tool Life of Metal-Cutting Tool

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Abstract. The paper is focused on turning of structural steels C45. Cutting tools were represented by carbide cutting inserts without coatings, with reference coating TiAlN, as well as with multilayered composite nano-structured coatings Ti-TiN-(TiCrAl)N and Zr-ZrN-(ZrCrNbAl)N (of different thickness of 3-7 μm). The following studies of the properties of coated tools were carried out: measurement of microhardness and strength of adhesion bonds in the "tool-coating" system and investigation of elemental and phase compositions of coatings. The cutting tests were carried out at the following cutting modes: f = 0.2 mm/rev; ap = 1.0 mm; vc = 200, 250, 300, 350 and 400 m/min.

1. Introduction

Wear-resistant coatings are actively and successfully applied to modify superficial layer of tool materials and thus to increase performance properties of cutting tools. On the one side, the use of modifying coatings makes it possible to increase tool life, while on the other side, that can significantly increase cutting modes and, first of all, the cutting speed [1-5]. Coating thickness is an important indicator that significantly affects the performance properties of metal cutting tools. The choice to select the optimum coating thickness for different machining conditions was studied by a number of researchers. In particular, Klocke et al [6] note that carbide cutting tools with thicker PVD coatings are characterized by longer tool life and that contributes to reduction of production costs. Mean while, Messier et al [7] showed that when monolayered coating is deposited, its grains grow with increase in its thickness. Accordingly, superficial hardness of monolayered coating will decrease with increase in its thickness [6]. It can also be assumed that mechanical strength of thin coatings will be higher than that of thicker coatings. It is shown that nominal superficial hardness, superficial yield and maximum superficial strength decrease with an increase in coating thickness [6]. Bouzakis et al [7-10] studied the influence of thickness for coating (TiAl)N (coating with thickness of 2-10 μm was studied) on tool life of a carbide tool when turning steel at various cutting modes. It is found that tool life improves with an increase in coating thickness. Proceeding from the above, it can be noted there is some kind of "bipolar" opinion on coating thickness. On the one side, a number of authors argue that tool life improves with an increase in coating thickness (up to 10 μm), while other authors note a marked decrease in the performance properties of a coating as its thickness increases. Meanwhile, the influence of thickness of a multilayered nano-structured coating on tool life was in fact not studied. The purpose of this study was to investigate the influence of wear-resistant layer thickness and elemental composition of a coating on tool life at various cutting speeds (speeds of 250, 300, 350 and 400 mmin-1 were considered).

2. Materials and experiments

For the comparative tests, two types of multilayered nano-structured coatings were selected: Ti-TiN-(TiCrAl)N and Zr-ZrN-(ZrCrNbAl)N, each with three different thickness (3, 5 and 7 μm). These coatings were selected as the most effective ones in accordance with the results of previous tests [11-15]. The monolayered non-nano-structured coating TiAlN with thickness of 4 μm, as well as carbide uncoated insert were selected as an object of comparison. These coatings were deposited on carbide inserts with square shape (SNUN ISO 1832:2012) and with the following geometric parameters of the cutting part: $\gamma = -8°$, $\alpha = 8°$, $K = 45°$, $\lambda = 0$, and $R = 0.8$ mm. For deposition of coating, a vacuum-arc VIT-2 unit [11,13] was used, which was designed for the synthesis of coatings on substrates of various tool materials. The unit was equipped with an arc evaporator with filtration of vapor-ion flow, which was named filtered cathodic vacuum-arc deposition (FCVAD) in this study [13], and was used for deposition of coatings on tools to significantly reduce the formation of the droplet phase during coating.The cutting tests were carried out at the following cutting modes: f = 0.2 mm/rev; ap = 1.0

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mm; vc = 250, 300,350 and 400 m min-1. Tool failure criterion was flank wear l and VB = 0.4 mm. For microstructural studies of samples of carbide with coatings, a raster electron microscope FEI Quanta 600 FEG was used. To perform X-ray microanalysis, the study used characteristic X-ray emissions resulting from electron bombardment of a sample. The hardness (HV) of coatings was determined by measuring the indentation at low loads according to the method of Oliver and Pharr [16]. The adhesion characteristics were studied on a Nanovea scratch tester. The tests were carried out with the load linearly increasing from 0.05 N to 40 N.

3. Results and discussions

The results of the main parameters of coatings are shown in Table 1.

Table 1. Main parameters of the coatings under study.

Type of coating	Coating thickness	Hardness	Strength of adhesion bond to substrate
TiAlN	4 (±0.8)μm	30.3GPa	30.1 N
Ti-TiN-(TiCrAl)N	3 (±0.7)μm	32.7 GPa	34.2 N
Ti-TiN-(TiCrAl)N	5 (±0.6)μm	32.2 GPa	35.0 N
Ti-TiN-(TiCrAl)N	7 (±0.6)μm	33.5 GPa	34.8 N
Zr-ZrN-(ZrCrNbAl)N	3 (±0.6)μm	29.4 GPa	32.6 N
Zr-ZrN-(ZrCrNbAl)N	5 (±0.5)μm	30.1 GPa	33.1 N
Zr-ZrN-(ZrCrNbAl)N	7 (±0.5)μm	30.2 GPa	33.2 N

From the data provided, it can be seen that all the coatings under study are characterized by sufficient adhesion to substrate and microhardness, corresponding to the usual values for these coatings. Meanwhile, adhesion of multilayered coatings under study is slightly higher than that of monolayered coating TiAlN, and that can be explained by the presence of a specific adhesive layer in the structure of multilayered coatings [13]. The structures of coatings on cross-section are shown in Figures 1-2.

It can be seen that monolayered coating TiAlN has no nano-structure, while coatings Zr-ZrN-(ZrCrNbAl)N and Ti-TiN-(TiCrAl)N show a clear nano-structure of wear-resistant layer, and a transition layer without nano-structure can also be clearly seen. An adhesive layer cannot be determined on Figures due to its small thickness (about 20 nm).

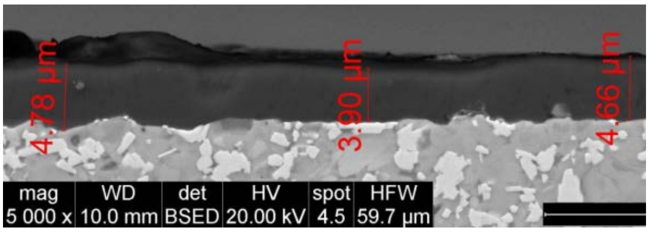
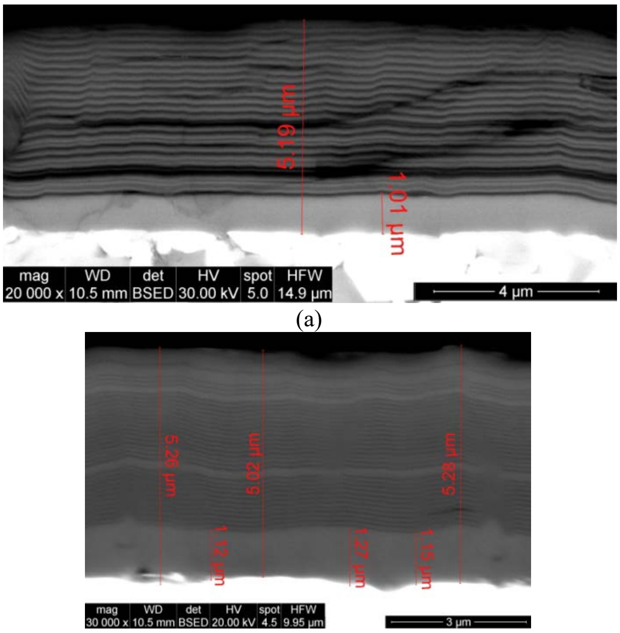


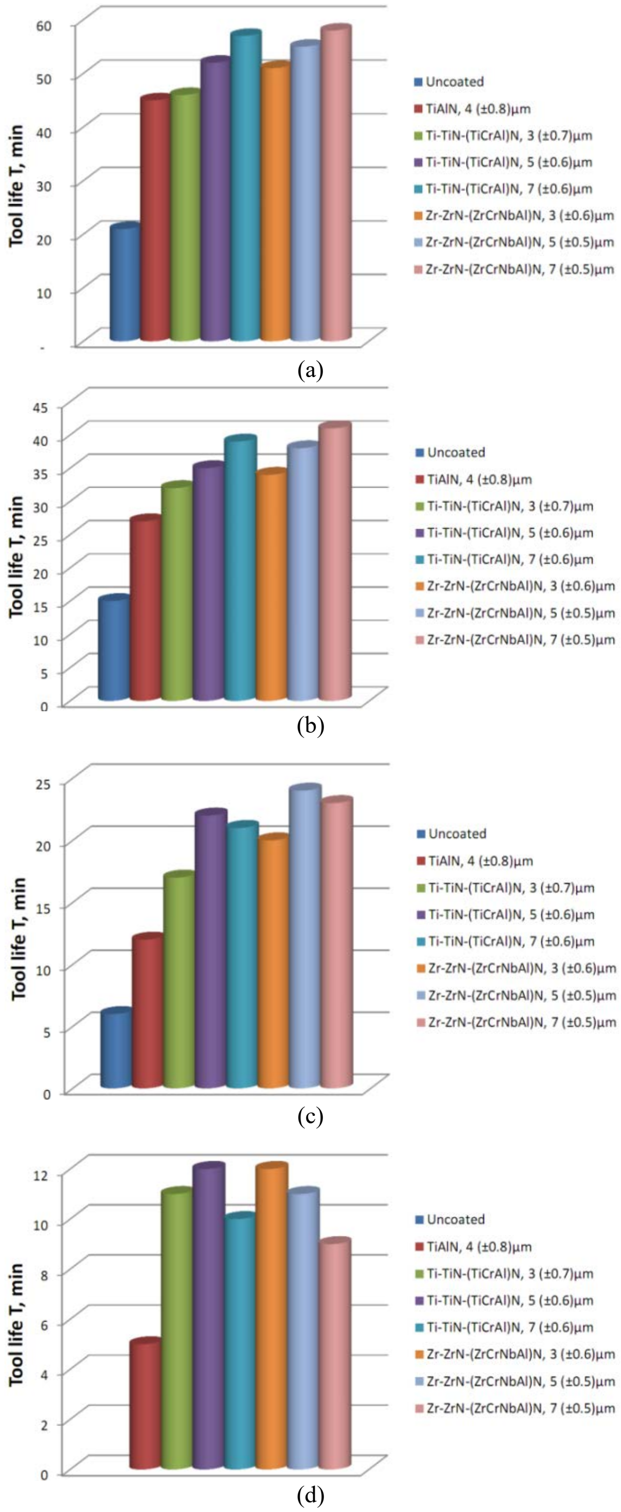
Fig. 1. Structure on cross-section of coating TiAlN, with thickness 4 (±0.8) μm.



(a)

(b)

Fig. 2. Structure on cross-section of coatings Zr-ZrN-(ZrCrNbAl)N (a) and Ti-TiN-(TiCrAl)N (b) with thickness of about 5 μm.



(a)

(b)

(c)

(d)

Fig. 3. Tool life of tools with coatings under study and of uncoated tools at cutting speeds of vc = 250 (a), 300(b), 350 (c) and 400 (d) mmin-1(f = 0.2 mm/rev; ap = 1.0 mm, longitudinal turning of steel C45).

The results of cutting tests for uncoated tool and tools with coatings under study are shown in Figure 3. On the basis of the results obtained, it can be noted that:

- At cutting speed of vc = 400 mmin-1, an uncoated insert shows excess flank wear after the very first minute of cutting and that indicates uncoated tools cannot be used under these cutting modes.
- If at cutting speed of vc = 250 mmin-1, a tool with monolayered coating TiAlN shows tool life close to durability of multilayered coatings with thickness of about 3 µm, then with increasing cutting speed, tool life of a tool with such coating decreases significantly faster than tool life of a tool with multilayered nano-structured coating. At cutting speed of vc = 400mmin-1, a tool with monolayered coating TiAlN operates significantly worse than tools with multilayered nano-structured coatings Zr-ZrN-(ZrCrNbAl)N and Ti-TiN-(TiCrAl)N under study.

If at cutting speed of vc = 250 mmin-1 the longest tool life is shown by tools with thicker coatings, then as the cutting speed increases, the picture begins to change and tools with thinner coatings show better results (especially for coating Zr-ZrN-(ZrCrNbAl)N at vc = 400 mmin-1). This phenomenon can be explained by the growth of internal stresses in the structure of coating with an increase in cutting speed, and the process in especially active in thicker coatings. While there are currently no methods for direct measurement of internal stresses in the structure of coating with its thickness of several µm, there are indirect methods to detect growth of those stresses, at least on qualitative level. Find more details on the issue in [16,18].

4. Conclusions

The use of multilayered nano-structured coatings (in particular, coatings Zr-ZrN-(ZrCrNbAl)N and Ti-TiN-(TiCrAl)N) makes it possible to increase cutting speed in turning of structural steels. Advantages of cutting tools with these coatings are especially obvious at high cutting speeds (in particular, vc = 400 mmin-1). If at lower cutting speeds the longest tool life is shown by tools with thicker coatings (of about 7 µm), then with an increase in cutting speed (especially at vc = 400 mmin-1) the longest tool life is shown by a tool with thinner coating (of about 3 µm). This phenomenon may be explained by more significant growth of internal stresses in thick coatings with an increase in cutting speeds. High internal stresses result in formation of internal cracks and interlayer delamination that ultimately lead to destruction of coating.

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