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Structure and properties of cathodic vacuum arc deposited NbN and NbN-based multi-component and multi-layer coatings

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Abstract

Binary Nb–N coatings, ternary Ti–Nb–N and Zr–Nb–N, and multi-layer TiN/NbN coatings consisting of up to 100 alternating TiN and NbN layers, were deposited onto WC–Co substrates, using two different vacuum arc deposition (VAD) systems: with and without magnetic guiding of the metal plasma flow. Binary Nb–N coatings were fabricated by deposition of metal plasma produced by a Nb cathode in a background of reactive nitrogen gas at different pressures, *P*. Ternary coatings were fabricated at co-deposition of plasmas originating from two different cathode materials. Multilayer coatings were fabricated by alternatively depositing plasmas of Ti and Nb in reactive nitrogen gas. The crystalline coating structure, phase composition, hardness and critical load for coating failure were studied.

For binary Nb–N coatings fabricated using both deposition systems, the phase composition, the Vickers hardness, HV, and the critical load strongly depended on the deposition pressure. Using VAD with magnetic plasma guiding, the highest HV of ~42 GPa was measured for coatings deposited at low nitrogen pressure. These coatings contained a hexagonal β-Nb_2N phase and had a relatively low critical load. The highest critical load and HV ~ 38 GPa were obtained for coatings consisted of a single phase NaCl-type cubic δ-NbN structure, deposited at a higher nitrogen pressure. The structure and properties of Nb–N coatings deposited using VAD without magnetic plasma guiding had a similar correlation with the deposition pressure, however, their hardness values were lower.

Ternary Ti–Nb–N and Zr–Nb–N coatings fabricated by both deposition processes had a single phase cubic NaCl-type structure and the hardness higher than that of the binary nitrides TiN, ZrN and NbN. The hardest coatings, HV ~ 51.5 Pa, deposited with magnetic plasma guiding had a single-phase cubic δ-(Ti,Nb)N structure and a Ti:Nb ratio of ~50:50 (at.%).

Multilayer coatings TiN/NbN consisting of 20–40 alternating TiN and NbN layers with total thickness of 4–5 μm increased the life time of cemented carbide cutting inserts at turning tough Ni-base alloys by 2–7 times relative to uncoated cutting tools, while conventional vacuum arc deposited TiN coatings were not effective in machining of these alloys.

Keywords: NbN coatings; vacuum arc deposition; hardness; multi-component coatings; multi-layer coatings

1. Introduction

Thin hard coatings based on nitrides of IV–VI group transitional metals deposited by different techniques are now widely used as wear resistant coatings, in particular, on cutting tools. Among binary nitrides, NbN coatings are of increasing interest because of their extremely high hardness. Despite the fact that the hardness of bulk NbN (HV = 14 GPa) is much lower than the bulk hardness of other nitrides (e.g. TiN and ZrN [1,2]), the hardness of cathodic vacuum arc deposited (VAD) NbN coatings is usually significantly higher than other binary nitrides. Andrievsky et al. [3] showed that the Vickers microhardness, HV, of VAD NbN coatings (HV = 33–34 GPa) was higher than that for other binary nitride coatings, e.g. TiN, ZrN and CrN. Similarly, Zhitomirsky et al. [4] showed that NbN coatings (HV ~ 38 GPa) were much harder than other binary nitride coatings, for example, TiN [5,6] and ZrN [7], fabricated using the same deposition system and similar deposition conditions. Martin and Bendavid [8] and Bendavid et al. [9] reported even higher hardness values of 45–48.5 GPa (ultra-microindentation system equipped with Berkowich indenter) of their NbN deposited by filtered vacuum arc deposition. In their studies, the hardness increased with increasing negative substrate bias voltage, V_b, and then saturated at $V_b \approx -100$ V. The high hardness was correlated with high compressive stress in their coating [9].

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Data on the tribological properties of NbN, as well as of NbN-based multi-component and multi-layer coatings, and the cutting performance of tools with these coatings, is limited and often contradictory. Rutherford et al. [10] studied TiN, NbN, as well as multi-component Ti–Nb–N and multi-layer coatings with alternating TiN and NbN layers, deposited by reactive VAD on high speed steel (HSS) substrates. They showed that NbN exhibited the highest hardness and the highest wear resistance among the coatings in their studies.

However, generally, NbN is not considered to be a good coating for cutting tools. Larsson et al. [11,12] showed that their NbN coatings fabricated by dc sputtering, were much harder than TiN, but they mentioned, however, that pure NbN "is not available on the market" as a coating for cutting tools, while TiN is one of the most widely used coatings for cutting tool applications [12]. Moreover, Selinder et al. [13] reported that pure NbN coatings on cemented carbide tools had poor cutting performance and brittle failure.

Contradictory results were presented also for multi-component VAD (Ti,Nb)N coatings, e.g., co-deposited from Ti and Nb plasmas in a nitrogen reactive gas. Grimberg et al. [14] reported an extremely high microhardness (47–51 GPa) of ternary $(Ti_{0.5}Nb_{0.5})N$ coatings having a single-phase NaCl-type structure. This is in contrast to the above mentioned study by Rutherford et al. [10], where the (Ti,Nb)N had the lowest hardness and wear resistance among the coatings in their study. Low hardness of VAD $(Ti_{0.7}Nb_{0.3})N$ and $(Ti_{0.85}Nb_{0.15})N$ coatings was also reported by Ross et al. [15] and Vancoillle et al. [16], although cutting performance of drills with these coatings was better than that with conventional TiN coating [15].

It was shown that multi-layer coatings consisting of 100–500 alternating TiN and NbN layers with layer thickness of 5–15 nm, and total coating thickness of few μm, have a superlattice structure [17–22], and they are significantly harder than single-layer binary TiN and NbN coatings. Chu et al. [17,19] and Sproul [20] reported a maximum Vickers microhardness of as high as HV = 52 GPa for their TiN/NbN superlattices fabricated by magnetron sputtering. Generally, in their research [17,19], the hardness was in the range of 12–52 GPa, and strongly depended on the nitrogen gas pressure, the negative bias voltage, V_b, applied to the substrate and the superlattice period Λ. They showed that with increasing Λ ($V_b = -150$ V), HV first increased, passed the maximum of HV = 50–52 GPa at $\Lambda = 5–8$ nm, and then steeply decreased to HV < 35 GPa with further Λ increase. However, Andrievsky et al. [3] observed hardness of HV ~ 49 GPa for VAD TiN/NbN consisting of only 20 alternating layers. In contrast to this, in studies of sputtered TiN/NbN superlattice coatings by Larsson et al. [11,12,23], HV was in the range of 32–34 GPa, i.e., approximately the same or even a little lower than that of pure NbN. Also, Zeng [22] observed HV ~ 40 GPa, which is significantly lower than the HV = 52 GPa reported by Chu [17,19].

Only limited information is available on wear and cutting tool performance of TiN/NbN multi-layer coatings. Selinder et al. [13] observed a superior performance of TiN/NbN superlattice coatings in cutting tool applications. Zeng [22] reported that the TiN/NbN wear rate was lower than that of TiN and NbN, and mentioned, however, that wear protection of this coating was below expectation according to its superhardness. Moreover, in his research, the critical load for coating failure decreased with increasing hardness. Larsson [12] and Nordin [23] reported somewhat better wear resistance of TiN/NbN multi-layers, compared to TiN, and proposed that these coatings are a good choice for applications where abrasive wear is the predominant wear mechanism. However, again it should be noted that the hardness and wear resistance of superlattices in their studies were of the same order as their pure NbN coatings.

The complicated Nb–N phase diagram [24], the strong dependence of Nb–N crystalline structure and texture on the deposition parameters, (particularly background nitrogen pressure [4,17], substrate bias voltage [9], and even layer thickness [19]), lead to different, often contradictory and even confusing, data on binary NbN and NbN-based multi-component and multi-layer coatings. For these coatings fabricated by VAD, up to now there is lack of experimental data on the effect of deposition parameters on the coating properties, as well as unambiguous recommendations for their optimal fabrication and use as wear resistant coatings, particularly, for cutting tool applications.

Binary Nb–N coatings and NbN-based multi-component and multi-layer coatings deposited by a VAD process with free expansion of the plasma beam, as well as the performance of cutting tools with these coatings, were studied by the author in 1980s at G.V. Karpenko Institute of Physics and Mechanics (IPM) of the Ukrainian Academy of Sciences (Lvov, Ukraine, former USSR). In 1990s the studies were continued at Tel-Aviv University (TAU) in Israel, using a triple cathode VAD system with magnetically guided plasma beam [4,5,14]. However, the IPM results mainly were not published previously. In this paper, the results of experimental studies of vacuum arc deposited binary Nb–N coatings, ternary (Ti,Nb)N and (Zr,Nb)N, and multi-layer TiN/NbN coatings consisting of alternating TiN and NbN layers, performed by the author during 20 years at two academic institutions, IPM and TAU, will be presented and discussed in light of cumulative research data relevant to these coatings. The cutting performance of cemented carbide tools with nitride coatings performed at IPM, will be also presented.

2. Experimental set-up and procedure

Binary NbN, ternary (Ti,Nb)N and (Zr,Nb)N, and multi-layer TiN/NbN coatings consisting of up to 100 alternating layers were fabricated using two different VAD systems: (1) the IPM VAD system, with free plasma expansion, and (2) the TAU VAD system with magnetically guided plasma flow.

2.1. VAD system with free expansion of the plasma beam at IPM

The deposition system used at IPM was similar in most features to the "Bulat-3"-type VAD system, which was standardly manufactured for the cutting tool industry in the former USSR at the beginning of 1980s. Three vacuum-arc plasma sources,