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Wear behavior of adaptive nano-multilayered TiAlCrN/NbN coatings under dry high performance machining conditions

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Abstract

Application of quaternary nitride nano-multilayered coatings results in significant improvements in tool life as well as wear behavior of ball nose end mills under severe conditions of dry high speed machining of hardened H13 steel (HRC 55–57). Tool life of different nano-multilayered TiAlCrN-based coatings with addition of transitional metals based (of V and VI groups) nitride layers has been compared. Tool life of TiAlCrN/NbN coating was found to be higher than compared to the other nano-multilayered coatings. Investigation of surface structure characteristics of the TiAlCrN/NbN coating using Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), X-ray Photoelectron Spectroscopy (XPS) and High Resolution Electron Energy Loss Spectroscopy (HREELS) has been performed. The properties of the coatings such as microhardness, modulus of elasticity, coefficient of friction and oxidation stability at elevated temperatures were also studied. Cutting forces at the tool/workpiece interface have been measured in-situ. Temperatures on the surface of cutting tools were evaluated. The features of friction and wear behavior as well as mechanisms of tribo-adaptation of TiAlCrN/NbN nano-multilayered coatings were outlined.

Keywords: PVD coating; Nano-multilayered coatings; Wear resistance; High performance machining

1. Introduction

Maintaining high performance dry end milling of hardened tool steels with hardness within 55–60 HRC is a challenge [1,2]. The key point to it is productivity of the machining process [1]. Milling of forging dies and molds in a fully hardened condition leads to significant cost reduction of this time consuming operation. That is why a major trend in modern machining is elevating aggressive cutting conditions, primarily by means of higher cutting speeds. During high performance machining, severe frictional conditions occur associated with high stress and temperatures, which are generating on the cutting tool surface, and lead to excessive wear rate of cutting tools [3].

Advanced cutting tools that could reliably work under very aggressive cutting conditions are critically needed. This could be done by the application of solid carbide cutting tools with advanced hard PVD coatings, which are specifically designed for severe applications.

Nano-multilayered coatings, which are considered in this paper, have a specific structure consisting of alternating nano-layers of various compounds [4–8]. This structure of the coating results in outstanding physico-mechanical properties especially at high temperatures and under harsh environmental attack that is very important for the specific applications associated with severe frictional conditions of high performance machining [9–20]. This application demands higher thermal stability as well as higher hardness of the coating [21–23]. The thermal behavior of the multilayer coating is affected by the presence of interfaces as compared to the single layer coatings [24].

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Table 1
Cutting data for testing of the quaternary TiAlCrN/Me_xN nano-multilayered coating under conditions of dry high performance machining

Type of cutting operation	Cutting data				
	Speed (m/min)	Feed (mm/flute)	Depth of cut (mm)	Workpiece material	Tooling
Ball nose end milling	300–400	0.06	Axial depth: 5.0; radial depth: 0.6	Tool steel H13 (HRC 55–57)	The carbide ball nose end mills (2 flutes, 10 mm diameter, Mitsubishi)

This paper is focused on investigating friction and wear behavior of the nano-multilayered coating that contain alternating TiAlCrN nano-layers and the nano-layers that are based on the nitrides of transitional metals of V and VI group. These nitrides are most widely used to improve service properties and adaptability of the nano-multilayered coatings [8,25–31,36–38]. Investigations of nano-layered coatings, which contain VN [25], NbN [26], TaN [27–29], CrN [30], and WN [8] nano-layers are presented in literature. There is only a limited amount of information about wear resistance of nano-multilayered coatings under dry high performance machining conditions [30–31]. However literature data show that V and Mo nitride content nano-multilayered coatings can be excluded from the investigations of wear behavior under severe conditions outlined above. The reason for this is the following. We have to bear in mind that under severe conditions of dry high performance machining, the temperature within the cutting zone is very high, within 850–1000 °C and above [3,34,35]. Mo is an analogue of W that forms nitride with lower thermal stability and very high rate of oxidation at elevated temperatures [36]; V also forms the oxide that melts at the indicated temperatures [37]. It was known from the previous study that the formation of the liquid lubricating films is not beneficial to the aggressive cutting conditions under the study [38].

The goal of this research is the following: 1) to compare tool life of the nano-multilayered coating that contain alternating TiAlCrN and nano-layers, which are based on the nitrides of transitional metals of V and VI groups under aggressive cutting conditions; 2) to perform comprehensive investigation of micro-mechanical and tribological properties of the nano-multilayered coating at elevated temperatures; 3) explain a role of Nb addition to the composition of the TiAlCrN/NbN nano-multilayered coating.

2. Experimental details

An R&D-type hybrid coater (Kobe Steel Ltd.) was used in this study. An arc source (plasma-enhanced type [32]) and an Unbalanced Magnetron (UBM) sputtering source were installed in a counter-facing manner. Various substrates were used for the coatings deposition such as: mirror polished WC-Co cutting inserts for micro-mechanical properties measurements; ball nose Mitsubishi end mills (two flutes, 10 mm diameter) for tool life studies as well as gamma-TiAl intermetallic samples for evaluation of short-term oxidation resistance. A $Ti_{0.25}Cr_{0.10}Al_{0.65}$ target manufactured by a powder metallurgical process [32] were used as the arc cathode, while transition metallic targets made of Nb, Ta, Cr W were used as sputtering sources. Details of deposition technique of the nano-multilayered coating are published elsewhere [8].

Coatings were subjected to compositional (EDS), structural (SEM) and mechanical (micro-indentation) analysis [33]. Indentation hardness was measured using a nano-indentation instrument (Elionix ENT-1100) with a Berkovich type diamond indenter. 30 indentations were performed on each coating under the loads 60 mN. No thermal drift correction was used, since this instrument was installed in a thermally regulated chamber in which temperature drift rate is less than 0.1 °C/10 s and one indentation measurement took about 10 s.

Oxidation tests have been performed at 900 °C in air for 1 h.

The coefficient of friction vs. temperature was determined with the aid of a specially designed apparatus described in [15]. No less than three tests were performed for each kind of coating. The scatter of the friction parameter measurements was found to be around 5%.

Cutting tests have been performed under ball nose end milling conditions during machining of the hardened AISI H13 tool steel (HRC 55–57). Cutting data is presented in Table 1. During the tests the cutting forces were measured and the chips were collected. The color of chips changes with temperature. Based on the relationship between the color of chips and chip temperature [33,34] the chip temperatures were estimated.

To understand the physical mechanism associated with the phenomena that are taking place at the cutting tool/workpiece interface, the chemical composition of the tribo-films formed was studied by means of X-ray Photoelectron Spectroscopy (XPS), using an ESCALAB MK2 (VG) unit. The spectrometer was equipped with a hemispherical energy analyzer. X-ray tube with monochromatic Al K_α radiation ($h\nu = 1486.6$ eV) was used

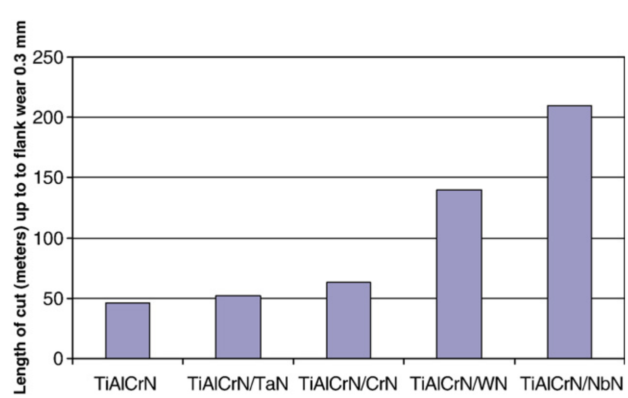

Fig. 1. Comparative tool life of the mono-layered TiAlCrN PVD coating as well as nano-multilayered TiAlCrN-based coatings with various transition metal nitride layers under high performance dry machining conditions (see Table 1).