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Wear behavior of ZrAlN coated cutting tools during turning

L. Rogström [a,*], M.P. Johansson-Jõesaar [a,b], L. Landälv [c,d], M. Ahlgren [d], M. Odén [a]

[a] Nanostructured Materials, Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-581 83 Linköping, Sweden
[b] SECO Tools AB, SE-737 82 Fagersta, Sweden
[c] Thin Film Physics, Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-581 83 Linköping, Sweden
[d] Sandvik Coromant, SE-126 80 Stockholm, Sweden

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ABSTRACT

In this study we explore the cutting performance of ZrAlN coatings. WC:Co cutting inserts coated by cathodic arc evaporated $Zr_{1-x}Al_xN$ coatings with x between 0 and 0.83 were tested in a longitudinal turning operation. The progress of wear was studied by optical microscopy and the used inserts were studied by electron microscopy. The cutting performance was correlated to the coating composition and the best performance was found for the coating with highest Al-content consisting of a wurtzite ZrAlN phase which is assigned to its high thermal stability. Material from the work piece was observed to adhere to the inserts during turning and the amount of adhered material and its chemical composition is independent on the Al-content of the coating.

1. Introduction

Hard and wear resistant coatings are widely used to prolong the tool life in cutting applications. Many of the frequently used physical vapor deposited (PVD) coatings are based on the TiN system, which can be alloyed with for example Al, Si and Cr to enhance the mechanical properties and the wear resistance [1–7]. One of the most commonly used PVD coating materials is TiAlN, for which the cubic (c) solid solution TiAlN phase decomposes as the coating is exposed to high temperatures, resulting in a fine nanostructure that improves the mechanical properties of the coating [8–10]. Thus, c-TiAlN coated tools typically exhibit good wear resistance [11,12]. The formation of wurtzite (w)-AlN phase in many of these materials, e.g. TiAlN and CrAlN, deteriorates the hardness and considerably reduces the wear resistance [11,13]. In contrast, the presence of w-AlN in ZrAlN coatings can improve the hardness [14]. ZrAlN is a much less explored material system, partly due to its large miscibility gap between c-ZrN and c-AlN, which makes it difficult to grow a solid solution of c-ZrAlN, except for low Al-contents [15,16]. Instead, the ZrAlN coatings have cubic or wurtzite structure depending on Al-content where in both cases the coatings have shown to have high hardness also after being exposed to high temperatures [14,16–18]. Recently we reported on the presence of spinodal decomposition in w-ZrAlN coatings, a high temperature behavior which may be favorable for cutting applications [19].

Here, we study the wear of inserts coated with four different ZrAlN coatings by electron microscopy techniques. The results show that the main wear mechanism is abrasive wear of the coating. In addition, plastic deformation of the coating occurs both close to the cutting edge and in the crater region. The higher thermal stability of the wurtzite structure $Zr_{0.17}Al_{0.83}N$ coating decreases the wear rate compared to the coatings with lower Al-content. The chemical composition of the work piece material that adheres to the tool surface changes with distance from the cutting edge. Both the thickness and the chemical composition of the adhered material are found to be independent on the Al-content of the coating.

2. Experimental details

$Zr_{1-x}Al_xN$ coatings were deposited on WC–10 wt.% Co inserts (ISO geometry CNMA120412 with a flat rake face) using an Oerlikon Balzers RCS arc-evaporation system. The depositions were performed at a temperature of 400 °C in a mixed flow of nitrogen and argon at a total pressure of 1.7 Pa. A negative bias of 40 V was applied to the substrates which were placed on a 3-fold rotation fixture. Four depositions were made using 160 mm cathodes of $Zr_{1-x}Al_x$ alloys with $x = 0$, $x = 0.35$, $x = 0.50$ and $x = 0.83$, respectively. The arc current was 160 A, 160 A, 150 A, and 120 A for the four cathodes respectively. Before deposition of ZrAlN, the substrates were cleaned by Ar ion etching and an approximately 50 nm thick adhesion layer of TiN was deposited.

The metal cutting performance of ZrAlN coated inserts was tested by using a work piece material of hot rolled and annealed carbon engineering steel, C45E (AISI 1045, 170HB), in a continuous, longitudinal turning

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[*] Corresponding author.
E-mail address: linro@ifm.liu.se (L. Rogström).

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Table 1
Chemical composition of the C45E work piece material where Fe is the balancing element.

Element	C	Mn	Si	P	S	Cu	Cr	Ni
Wt.%	0.43	0.79	0.227	0.012	0.022	0.03	0.06	0.02

Element	Mo	V	Sn	As	Ti	Al	Al met.	N
Wt.%	0.006	0.001	0.003	0.002	0.002	0.030	0.028	0.0052

operation. The chemical composition of the work piece material is shown in Table 1. Cutting tests were performed with cooling, and with a cutting speed v_c between 220 and 240 m/min while the feed and depth of cut were kept constant at $f = 0.2$ mm/rev and $a_p = 2$ mm, respectively. The lower speed was used to produce samples intended for electron microscopy studies, to ensure a longer contact time without complete wear of the coating. In addition to tests made on ZrAlN coated tools, a commercial SECO Tools CP500 TiAlN coating grade was used as reference and tested with the same cutting parameters. Note that this coating grade has an additional TiN top coating of approximately 200 nm. The evolution of tool wear, both flank- and crater wear, was examined with optical microscopy by interrupting, measuring and restarting the cutting test every minute. The crater wear is defined as the area of exposed substrate on the rake face and the flank wear as the length of the exposed substrate measured from the edge at the flank side. In addition, electron microscopy samples were prepared using the same cutting parameters for different cutting times in order to study the initial and intermediate stages of wear.

The structure of the as-deposited coatings was determined by X-ray diffractometry using θ–2θ geometry and Cu Kα radiation and a Philips diffractometer. The hardness of the coatings was determined by nanoindentation using a UMIS 2000 system equipped with a Berkovich indenter. 20 indents were made on polished, tapered cross sections (8° tapering angle) of each coating using a maximum load of 50 mN. The data was analyzed by the technique of Oliver and Pharr [20] and reported here are the mean value and the standard deviation from the 20 indents. The hardness was measured on as-deposited samples as well as samples annealed in vacuum for 2 h at 900 °C.

Worn inserts were studied in a scanning electron microscope (SEM) (Zeiss LEO 1550) equipped with an energy dispersive X-ray spectrometer (EDS) (Oxford X-Max). For EDS elemental mapping, an acceleration voltage of 20 kV was used. Fractured cross sections of the as-deposited coatings were studied in the SEM to determine the coating thickness. For selected worn coatings, samples for (scanning) transmission electron microscopy ((S)TEM) studies were prepared by a focused ion beam instrument (FIB) (Zeiss 1540 EsB). The prepared samples were studied in a FEI Technai G2 TF 20 UT microscope operated at 200 kV and equipped with a high angle annular dark field (HAADF) detector for STEM imaging.

3. Results and discussion

3.1. Structure and mechanical properties

Fig. 1 shows X-ray diffractograms of the as-deposited $Zr_{1-x}Al_xN$ coatings and Table 2 lists their crystal structure, thickness and mechanical properties. The coatings are labeled according to the cathode composition while the as-measured Al-content is expected to be slightly less due to re-sputtering of Al during growth [21,22]. The crystal structure, as determined by XRD and confirmed by selected area electron diffraction for the three crystalline coatings, changes from cubic for the ZrN and the $Zr_{0.65}Al_{0.35}N$ coatings to wurtzite for the coating containing the largest amount Al, $Zr_{0.17}Al_{0.83}N$. These findings are in good agreement with previous studies of ZrAlN coatings [16,23]. In the $Zr_{0.50}Al_{0.50}N$ coating, no diffraction peaks were observed by XRD, which can be expected as ZrAlN coatings with similar composition commonly have a nanocomposite (nc) structure consisting of a mixture of small cubic and hexagonal structured grains and amorphous phases [16,22].

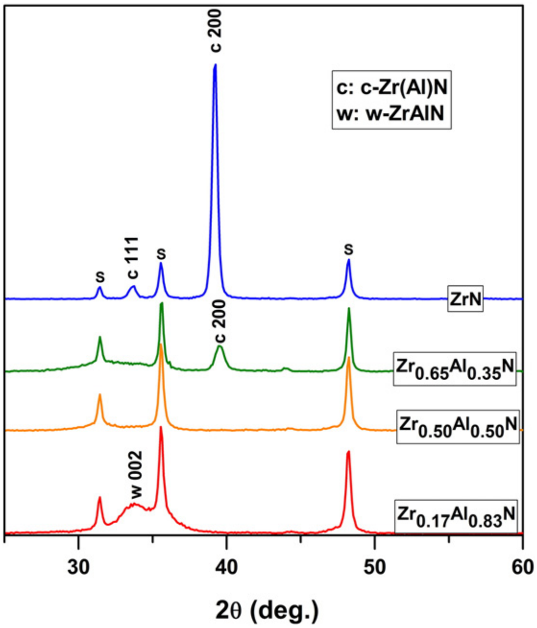

Fig. 1. X-ray diffractograms of the as-deposited $Zr_{1-x}Al_xN$ coated inserts. S marks the positions of peaks originating from the substrate.

The thickness of three of the coatings is similar, while $Zr_{0.50}Al_{0.50}N$ exhibits a lower thickness than the other ZrAlN coatings due to a lower deposition rate. The TiAlN reference coating has a considerable larger thickness than the $Zr_{1-x}Al_xN$ coatings and is merely used as a reference value of the lifetime of a commercial tool under the present cutting conditions (Section 3.3). The hardness of the ZrAlN coatings varies with Al-content, similar to what was observed in Ref. [16], and the highest hardness is found for the three single phase coatings. For evaluation of the thermal stability of the mechanical properties the hardness was also measured on samples annealed for 2 h at 900 °C. The highest hardness after annealing is found for the coating with a wurtzite structure, which may be related to the decomposition of this phase at high temperatures [16,19]. The elastic modulus derived from the indentation data decreases with Al-content which can be expected as the bulk value of the indentation elastic modulus is higher for c-ZrN ($E = 460$ GPa [24]) than for w-AlN ($E = 308$ GPa [25]).

3.2. Wear and adhered work piece material

3.2.1. Wear zones

Fig. 2 shows optical micrographs of the rake face of worn $Zr_{1-x}Al_xN$ coated inserts, with increasing Al content x, after turning for 1, 6 and 12 min at a cutting speed of $v_c = 240$ m/min. The crater wear is evolving with increasing turning time (from top-to-bottom in Fig. 2). In the case of c-ZrN and c-$Zr_{0.65}Al_{0.35}N$ the WC:Co substrate is exposed after 6 min (light gray) while this has not happened even after 12 of turning for the worn w-$Zr_{0.17}Al_{0.83}N$ coated insert, which implies an improved crater wear resistance. The thinner nc-$Zr_{0.50}Al_{0.50}N$ coating was completely worn through already after 7 min. A similar amount of notch wear at the depth of cut (marked with arrows) is apparent in all tested $Zr_{1-x}Al_xN$ coatings. Notch wear is generally understood as the effect of a strong abrasion between the work hardened machined surface and the cutting tool at the depth of cut.

Fig. 3a shows a secondary electron SEM micrograph of the rake face (crater wear region) of the c-ZrN coated insert, after 4 min of turning with a cutting speed of $v_c = 220$ m/min. The corresponding wear zones are schematically shown in Fig. 3b. At the position of the arrow, zone I (edge region) stretches from 0–0.3 mm from the cutting edge,