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Wear behavior and cutting performance of CrAlSiN and TiAlSiN hard coatings on cemented carbide cutting tools for Ti alloys

Yin-Yu Chang [1], Hsing-Ming Lai

Department of Mechanical and Computer-Aided Engineering, National Formosa University, Yunlin 632, Taiwan

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ABSTRACT

Recently, multicomponent CrAlSiN and TiAlSiN coatings have been developed in order to gain high hardness and good thermal stability. In this study, the influence of TiAlN, CrAlSiN and TiAlSiN coatings on the wear behavior and cutting performance of the carbide cutting tools was investigated in dry machining of a Ti–6Al–4V alloy. TiAlN, CrAlSiN and TiAlSiN coatings were deposited on tungsten carbide milling inserts by using cathodic arc evaporation. The deposited TiAlN, CrAlSiN and TiAlSiN possess high hardness of 31 ± 1 GPa, 36 ± 2 and 35 ± 2 GPa, respectively. After annealing at 700 °C in air, the hardness of the CrAlSiN and TiAlSiN still keeps as high as 35–36 GPa, while the hardness of TiAlN decreases to 26 GPa. The main wear modes for the TiAlSiN-, TiAlN coated- and uncoated tools are abrasion and adhesion. The nanocrystalline TiAlSiN coatings retard the tool wear as compared to the TiAlN-coated tools. At a high cutting speed of 350 m/min, the tool life of the CrAlSiN coatings exceeds the TiAlSiN-, and TiAlN-coated and uncoated tools by 2.9, 4.2 and 9.5 times, respectively. The CrAlSiN coatings show high wear resistances in dry machining of Ti–6Al–4V alloys, and thus possess the best cutting performance.

1. Introduction

Titanium (Ti) and its alloys are used extensively in aerospace industry, nuclear power industry, automotive industry and biomedical applications because of their high specific strength (strength-to-weight ratio) maintained at elevated temperature, fracture resistant characteristics, and exceptional resistance to corrosion [1]. Cutting of Ti alloys, such as Ti–6Al–4V alloys, has always been a topic of great interest for industrial production and scientific research worldwide. However, titanium alloys are known as difficult-to-machine materials, especially at higher cutting speeds. It is important to note that its low thermal conductivity may cause difficulties in heat dissipation during a cutting process, which results in high cutting temperature concentrated at a narrow region adjacent to the cutting edge. Another significant machining characteristic of the Ti–6Al–4V alloy is its high chemical reactivity. As a result, tool wear progresses rapidly and then reduces the tool life and deteriorates machining quality [2–6]. The hot surface at the cutting edge, with a high degree of cutting in contact with the tool surface, causes a very quick chemical reaction, and it is responsible for the excessive wear on the tool face. Titanium alloys are generally difficult to machine at cutting speeds over 30 m/min with high speed steel (HSS) tools, and over 60 m/min with cemented tungsten carbide tools [7]. Carbide inserts are especially useful in the milling operations due to their high toughness and hot hardness. The early tool wear of carbide inserts in machining of the Ti alloys, however, limits the use of these tools in hard machining applications. The only solution to use the carbide inserts in the cutting applications is to protect them with a corresponding suitable hard coating.

Since a few decades, TiN, CrN and TiAlN have been widely used as hard coating applications such as drills and milling inserts because of their high hardness, wear resistance, and chemical stability [8–11]. However, TiN coatings are limited for high temperature applications above 500 °C, which usually occurred during the high-speed dry machining process. This was the main reason in 1990s why TiN coatings were replaced by TiAlN coatings that had a higher hardness and was more oxidation resistant [12,13]. Recently, multicomponent coatings based on different metallic and non-metallic elements provide the benefit of individual components leading to a further improvement of coating properties. Multicomponent TiAlSiN coatings containing a small amount of Si (a few atomic percent) consisted of single B1 cubic phase and grain refinement was observed. The TiAlSiN coatings consisting of nanocrystalline TiAlN and amorphous silicon nitride have been developed to provide good thermal stability at temperature exceeding 800 °C [14–17]. The Si containing TiAlSiN coatings have significantly better oxidation resistance compared to the ones without Si. Preferential oxidation of Si was observed after the oxidation test and the Si-rich oxides acted as a diffusion barrier for further oxidation [18,19]. In addition, CrAlSiN coatings have been focused by several research groups for their high hardness and high temperature oxidation resistance [19–22]. R. Rafaja and P. Karvankova et al. [23–25] showed that the TiAlSiN and CrAlSiN coatings with Ti/(Ti + Al + Si) and Cr/(Cr + Al + Si) ratios being ~0.5

E-mail address: yinyu@nfu.edu.tw (Y.-Y. Chang).

[1] Tel.: +886 5 6315332; fax: +886 5 6315310.

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can possess hardness as high as 36–44 GPa. This implies that TiAlSiN and CrAlSiN can be used as wear-resistant coatings for dry machining applications [26,27].

In the present study, a cathodic arc ion plating system was used for the deposition of TiAlN, CrAlSiN and TiAlSiN coatings on tungsten carbide insert substrates. The tool wear and failure progression under high speed cutting conditions were analyzed in dry milling of Ti–6Al–4V alloys.

2. Experimental details

TiAlN, CrAlSiN and TiAlSiN coatings were deposited on polished tungsten carbide (WC/Co) samples and WC/Co milling inserts by using a cathodic arc evaporation system. The substrate samples and milling inserts were cleaned in an ultrasonic cleaner using acetone and alcohol for 30 min. A rotational substrate holder was located in the vacuum chamber. The rotational speed was fixed at 2 rpm. Before deposition, the sputtering chamber was pumped down from atmospheric pressure to a base pressure of 1×10^{-3} Pa using a combination of rotary pump and turbo molecular pump. Substrates were cleaned again by ion bombardment using a bias voltage of −800 V under Ar atmosphere of 1 Pa for 15 min. TiAlN coatings were deposited using TiAl (50 at.% of Ti and 50 at.% of Al) alloy targets in N_2 atmosphere. A dc arc current of 110 A was applied between the anode and the TiAl cathode. Chromium, titanium and AlSi (88 at.% of Al and 12 at.% of Si) alloy targets were used as cathodic arc sources to deposit the CrAlSiN and TiAlSiN coatings. TiN and CrN were deposited as interlayers of TiAlSiN and CrAlSiN, respectively, at N_2 pressure of 2.5 Pa and bias voltage of −100 V. Substrate bias voltage of −80 V and N_2 pressure of 2.5 Pa was used. The cathode current applied to Ti, Cr and AlSi targets was 100 A, to control the composition of the deposited CrAlSiN and TiAlSiN coatings. Substrate samples were heated by a radiant heater arranged inside the chamber, and the temperature of the sample during the deposition was controlled within the range of 400–430 °C. The thickness of the deposited coatings was controlled at 2.2 ± 0.3 μm with deposition time of 60 min.

For the machining experiment, the workpiece material was Ti–6Al–4V alloy with a dimension of 300 × 100 × 35 mm. The hardness of the Ti–6Al–4V alloy is HRc 35. The milling inserts were positioned on the cutter, produced by Chain Headway Machine Tools, with the designation of APKT100304PDFR-F01 to provide radial rake angle of 15°, cutting corner radius of 0.8 mm and clearance angle of 11°. The cutting tests were carried out by dry milling with a feed rate $(f_z) = 0.02$ mm/tooth, depth of cut $(a_p) = 0.3$ mm, and cutting speeds (V_c) of 150 m/min and 350 m/min. Compressed air at a room temperature of 27–28 °C was supplied at a pressure of 0.8 MPa during the cutting experiment. Since tool wear is the most important factor limiting tool lives, thus hampering employment of aggressive dry cutting conditions at high cutting speed, tool wear was measured using a microscope after a specific machining time period [28]. Once the tool wear was measured, the tool was remounted back on, and the machining procedure was repeated. The wear morphologies of the cutting edge were also examined with a JEOL JSM-6700F high resolution field emission scanning electron microscope (FESEM).

The chemical composition of the deposited coatings was determined by using a high resolution electron probe microanalyzer (FE-EPMA, JEOL JXA-8500F). The texture of the TiAlN, CrAlSiN and TiAlSiN films was examined by X-ray diffraction (PANalytical X'pert Pro MRD) with Cu radiation at a glancing angle of 0.5° for phase identification. The diffractometer was operated at 40 kV and 1 mA. The coating morphology and microstructure were investigated by using a JEOL JSM-6700F high resolution field emission scanning electron microscope (FESEM) and a field emission gun high resolution transmission electron microscope (FEG-HRTEM, FEI Tecnai G^2 20 S-Twin). To evaluate the hardness of the deposited coatings after high temperature oxidation, the deposited samples were annealed at 700 °C and 900 °C in air for 2 h. The heating rate was 5 °C/min and the samples were subsequently furnace-cooled. Hardness of the films were obtained using XP-MTS nano-indentation with a Berkovich indenter, under load-unloading condition, and measured as a function of indenter displacement using continuous stiffness measurement method. The maximum penetration depth was controlled at 220 nm, therefore, the influence of substrate on the measured hardness is negligible.

3. Results and discussion

3.1. Microstructure characterization of the as-deposited TiAlN, CrAlSiN and TiAlSiN coatings

Table 1 shows the chemical composition of the deposited TiAlN, TiAlSiN and CrAlSiN coatings, which are denoted as $Ti_{0.52}Al_{0.48}N$, $Cr_{0.47}Al_{0.46}Si_{0.07}N$ and $Ti_{0.55}Al_{0.40}Si_{0.05}N$, respectively. The nitrogen content of all the deposited coatings was 49.5 at.%–54.0 at.%. The CrAlSiN and TiAlSiN quaternary alloy coatings with Cr/(Cr + Al + Si) and Ti/(Ti + Al + Si) ratios being 0.47–0.55 were deposited to obtain optimal mechanical properties according to previous studies by R. Rafaja and P. Karvankova et al. [23–25]. Typical glancing X-ray diffraction spectra of the $Ti_{0.52}Al_{0.48}N$, $Cr_{0.47}Al_{0.46}Si_{0.07}N$ and $Ti_{0.55}Al_{0.40}Si_{0.05}N$ coatings are shown in Fig. 1. The XRD results showed that all the deposited coatings possess B1–NaCl crystal structure and have multiple orientations of (111), (200), (220) and (311). It corresponded with the results by Rafaja et al. [23] and Y. X. Wang et al. [28], which showed that the cubic structure remained with (Al + Si)/(Ti + Al + Si) content ratio lower than 0.6. In this study, the $Ti_{0.55}Al_{0.40}Si_{0.05}N$ deposited with (Al + Si)/(Ti + Al + Si) content ratio of 0.45 only showed B1–NaCl crystal phases and no hcp-AlN phase was found. Both $Cr_{0.47}Al_{0.46}Si_{0.07}N$ and $Ti_{0.55}Al_{0.40}Si_{0.05}N$ coatings showed a preferred (200) orientation as compared to $Ti_{0.52}Al_{0.48}N$. Containing Si into the coatings facilitated (200) growth orientation. The FWHM of the $Ti_{0.55}Al_{0.40}Si_{0.05}N$ (200) peak was 0.69°, and broadened with addition of Si compared to $Ti_{0.52}Al_{0.48}N$ (FWHM = 0.54°). It indicated crystallite size in $Ti_{0.55}Al_{0.40}Si_{0.05}N$ film was refined. Fig. 2 shows the high-resolution transmission electron microscopy (HRTEM) observation and the corresponding selected area electron diffraction (SAED) of the deposited $Ti_{0.55}Al_{0.40}Si_{0.05}N$. The deposited $Ti_{0.55}Al_{0.40}Si_{0.05}N$ exhibited interlayers of TiN to improve the adhesion strength. Our previous study [29] showed that the design of multilayered TiAlSiN/TiN in the lower part of the coating increased the resistance to plastic deformation due to the enhancement of interface contribution of TiAlSiN/TiN. As shown in the top image of Fig. 2, the $Ti_{0.55}Al_{0.40}Si_{0.05}N$ layer exhibited nanocrystalline structure due to the presence of Al and Si [29–31]. It was in agreement with the studies of V. Godinho et al. [32] and S.M. Yang et al. [33] showing that the nanocomposite microstructure was demonstrated by the formation of a face-centered cubic (Ti,Al)N phase, obtained by substitution of Al in the cubic titanium nitride phase, and an amorphous matrix at the column boundary regions mainly composed of Si and N. This is a result of the grain boundary effect on the hardness in the nanocomposite structure. Grain boundaries decrease the mobility of dislocations and, therefore, an increase in coating hardness is observed. The Si containing TiAlSiN coatings have better oxidation resistance compared to the TiAlN. Preferential oxidation of Si was observed after oxidation and the Si oxides acted as a

Table 1
Coating composition of the deposited $Ti_{0.52}Al_{0.48}N$, $Cr_{0.47}Al_{0.46}Si_{0.07}N$ and $Ti_{0.55}Al_{0.40}Si_{0.05}N$ coatings.

Samples	Coating composition (at.%)				
	Ti	Cr	Al	Si	N
$Ti_{0.52}Al_{0.48}N$	26.3	–	24.2	–	49.5
$Cr_{0.47}Al_{0.46}Si_{0.07}N$	–	22.5	22.0	3.4	52.1
$Ti_{0.55}Al_{0.40}Si_{0.05}N$	25.3	–	18.4	2.3	54.0