Surface & Coatings Technology 294 (2016) 54–61

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Tribo-films control in adaptive TiAlCrSiYN/TiAlCrN multilayer PVD coating by accelerating the initial machining conditions

Junfeng Yuan [a,*], Kenji Yamamoto [b], Danielle Covelli [c], Mohammed Tauhiduzzaman [a], Taib Arif [a], Iosif S. Gershman [d], Stephen C. Veldhuis [a], German S. Fox-Rabinovich [a]

[a] Department of Mechanical Engineering, McMaster University, 1280 Main St., W. Hamilton, Ontario L8S 4L7, Canada
[b] Kobe Steel Ltd., Kobe, Hyogo 651-2271, Japan
[c] Biointerfaces Institute, McMaster University, 1280 Main St., W. Hamilton, Ontario L8S 4L7, Canada
[d] Railway Transport Research Institute, Moscow 29851, Russia

A R T I C L E I N F O

Article history:
Received 6 December 2015
Revised 16 February 2016
Accepted in revised form 18 February 2016
Available online 22 February 2016

Keywords:
Nanolaminate TiAlCrSiYN/TiAlCrN PVD multilayer coating
Tribo-oxidation
X-ray photoelectron spectroscopy
Auger Electron Spectroscopy
Inconel 718, acceleration of initial conditions

A B S T R A C T

A nano- multilayer TiAlCrSiYN/TiAlCrN was deposited by Physical Vapor Deposition (PVD) on cemented carbide turning inserts. Assessment of the performance of the coated inserts in machining of DA718 Inconel was made at various cutting speeds during the initial, running-in stage of wear. Three types of machining conditions were used: i. Regular cutting speed (40 m/min) used in industrial practice; ii. Higher cutting speed of 60 m/min, and iii. Accelerated (higher speed followed by regular cutting speed). Comprehensive characterization of the tribofilms formed on the surface of the worn cutting tools was made using Auger Electron Spectroscopy and X-ray Photoelectron Spectroscopy analyses. SEM/EDS elemental mapping was used for evaluation of the wear patterns. It was shown that an initial short-term increase in the cutting speed during the running-in stage (condition iii) noticeably improves tool life. This is because during initial cutting at high speed, enhanced formation of protective/lubricious tribo-ceramic films on the friction surface takes place, with the subsequent slowdown in speed preventing total wearing out of the beneficial tribofilms. In this way, the tribofilm formation process can be enhanced at the start of the process and the benefits of these films can be realized over the life of the tool.

1. Introduction

The application of high speed machining processes to hard-to-machine aerospace materials brings a number of clear benefits; however it results in harsh tribological conditions and a very intensive tool wear rate [1,2]. In addition to the heavy cutting loads and elevated temperature, strong built up edge formation makes the processes more complicated. From a tribological viewpoint, built up edge is related to seizure on the friction surface, which is a catastrophic failure mechanism [3]. This leads to strong gradients in the characteristics of the friction surface, combined with significant instability of the frictional process [4,5]. Novel methods of cutting tool surface engineering, which are the major methods of tool life improvement, have been applied to address these challenges to provide efficient protection of friction surfaces under operation [4,6,7].

There are two approaches in the design of wear resistant coatings [6]. First, the coating is considered as a completely artificial system with minimal changes in its structure taking place through its interaction with the environment. In this case the hardness, oxidation, and thermal stability of the coating layer as deposited are used to consider the major properties responsible for wear resistance [8,9]. In contrast, the second approach involving an adaptive coating design, regards a coating as a surface-engineered tribological system that combines an artificial system (coating) and beneficial processes associated with friction and interaction with the environment that results in its adaptation to its environment. Adaptability, which significantly increases tool life, is a consequence of the beneficial structure and phase transformations that take place on the friction surface [10]. During the cutting process, tribo-oxidation of the coating layer plays a significant role in frictional behavior and wear resistance of the entire surface-engineered layer. During permanent tribofilm formation and wear, the coating layer is efficiently protected and lubricated. These processes provide tribological compatibility between the tool/workpiece system and resulting in reduced levels of surface damage of the cutting tool, generated in a longer tool life [11,12].

Physical vapour deposited (PVD) adaptive nanocrystalline multilayer TiAlCrSiYN/TiAlCrN coatings exhibit excellent tool life under severe cutting conditions [13]. This is true for the cutting of hard-to-machine materials; in particular for the machining of Ni-based superalloys [17]. Nickel-based superalloys have been widely applied for some demanding applications [3]. Inconel 718 superalloy, especially direct aged

* Corresponding author.

http://dx.doi.org/10.1016/j.surfcoat.2016.02.041
0257-8972/

Table 1
Structure and micro-mechanical characteristics of TiAlCrSiYN/TiAlCrN coatings at room and elevated temperatures.

Grain size, nm		20–40
Thickness, μm		2
Crystal structure		FCC nano-crystalline/laminated
Nano-layer thickness, nm		20–40
Microhardness, GPa	Room temperature	30
	500 °C	28

Inconel 718, belongs to the family of the most difficult-to-machine alloys due to high-temperature strength [3,4], low thermal conductivity, and propensity to work-harden during machining [5–9].

A special challenge for tribological compatibility is thus the ability to control tribofilm regeneration on the friction surface. This is related to the concept of adaptability [14] and is done by shifting the system, in the short-term, to severe frictional conditions during the running-in stage. This accelerates the formation of beneficial oxide on the surface of a tool in service.

This research is aimed to investigate the effect of initial high cutting speeds during the running-in stage when machining Ni-based super alloys using cutting tools with self-adaptive nanocrystalline multilayer TiAlCrSiYN/TiAlCrN coatings. This approach could provide the possibility of enhanced tribofilm formation on the tool initially and then prevent excessive wear of the tribofilm by slowing down to 'regular' machining conditions to prevent intensive wearing-out of the tribofilm layer. In this way the tribofilm formation can be controlled to improve the wear resistance of the surface engineered layer and thus enhance the productivity of the machining process by improving tool life.

2. Material and methods

2.1. Coating deposition

Nano-multilayered Ti0.2Al0.55Cr0.2Si0.03Y0.02 N/Ti0.25Al0.65Cr0.1 N coating was deposited using Ti0.2Al0.55Cr0.2Si0.03Y0.02 and Ti0.25Al0.65Cr0.1 targets, which were fabricated through a powdered metallurgical process. The thickness of each alternating nano-layer in the multilayer coatings was approximately 20–40 nm (Table 1) [13,15]. All inserts in this study were coated with the same coatings.

Coatings were deposited in an R&D-type hybrid PVD coater (Kobe Steel Ltd.) with a plasma-enhanced arc source. Samples were heated up to about 500 °C and cleaned through an Ar ion etching process. Ar–N_2 mixture gas was fed to the chamber at a pressure of 2.7 Pa with an N2 partial pressure of 1.3 Pa. The arc source was operated at 100 A for a 100 mm diameter × 16 mm thick target. Other deposition parameters were: bias voltage 100 V and substrate rotation 5 rpm. The thickness of the coatings studied was around 2 μm for the film characterization and cutting test work. Table 1 shows the structure and micro-mechanical characteristics of TiAlCrSiYN/TiAlCrN coatings at room and elevated temperatures [16].

Coated K313-CNGG432FS (in short CNGG) inserts with chip breaker (industry standard) were chosen for cutting tool life studies on a CNC lathe. The coated K313-SPG 422 flat inserts (in short SPG) were used for process characterization and additional laboratory studies to explain the nature of tool wear and tribofilm formation. The flatness of the SPG inserts allowed the accuracy of the data collected to be significantly improved. Since SPG inserts do not have a chip breaker with a complex shape, and the data obtained by surface analysis is much more accurate on this flat, mirror-polished rake face.

Table 3
AES parameters.

	Incident electron beam	Ar+ sputtering beam
Beam voltage	10 keV	1 keV
Beam diameter	100 nA	25 mA
Beam angle	30° from substrate normal	25° from substrate normal

2.2. Cutting experiments

Cutting experiments were performed at speeds of 40 m/min, 60 m/min and on accelerated test conditions (60 m/min at the beginning of machining followed by slowing down to 40 m/min for the remainder of the tool's life), which were designated as S40, S60 and S60/40 respectively. A cutting speed of 40 m/min can be characterized as usual industry practice. All cutting experiments were performed under wet machining conditions. All of the turning tests were carried out on the same Boehringer VDF 180 CNC lathe. The combination of feed = 0.1225 mm/rev and DOC = 0.25 mm was used for all experiments. Flank wear land width (Vb) was measured by a Mitutoyo Toolmaker's Microscope. Tool failure was determined to be at 300 μm and the tool life was characterized by its cutting length. The tool holder used in this work is a Kenna clamp DCLNL166DKC4. The major characteristics of the turning inserts, tool holder and the workpiece material are presented in Table 2.

2.3. Cutting tool surface characterization

Initial cutting using SPG inserts was performed in order to characterize the topography and to do the elemental mapping at 200 m length of cut in order to study the effects of tribofilms on tool wear. A TESCAN VEGA LSU scanning electron microscope (SEM) and EDX mapping were used for studying the microstructure and investigating wear mechanism of the worn tools. A Nikon Optical Microscope was used to study in the morphology of the rake face and for measuring the area of the crater wear.

To understand the mechanisms of tribofilms that take place at different cutting speeds, the SPG surfaces at the running-in stage were characterized by X-ray photoelectron spectroscopy (XPS). The XPS equipment consisted of a Physical Electronics (PHI) Quantera II spectrometer with a hemispherical energy analyzer, an Al anode source for X-ray generation, and a quartz crystal monochromatic for focusing the generated X-rays. The X-ray source was from a monochromatic Al K-α (1486.7 eV) at 50 W–15 kV and the system base pressure was between 1.0×10^{-9} Torr and 2.0×10^{-8} Torr. At the beginning, the samples were sputter-cleaned for 4 min with a 4 kV Ar+ beam before collecting the data. The beam for data collecting was 200 μm and all spectra were obtained at a 45° take off angle. A dual beam charge compensation system was utilized to ensure neutralization of all samples. The pass energy to obtain all survey spectra was 280 eV, while to collect all high resolution data it was 69 eV. The instrument was calibrated with a freshly cleaned Ag reference foil, where the Ag 3d5/2 peak was set to 368 eV. All data analysis was performed in PHI Multipak version 9.4.0.7 software.

Auger depth profile spectroscopy was used to analyze the thickness of the tribofilms on the worn SPG surface for the S60 samples. The sputtering rate and depth of tribofilm were calculated from the sputtering rate of SiO_2. This was performed on a Palkin Elmer PHI650 scanning AES and the primary parameters are shown in Table 3. The sputtering rate was 1 nm/min at the beginning and 2 nm/min after

Table 2
Cutting experiments.

Machining operation	Cutting tool substrates	Workpiece material	Workpiece Hardness	Tool holder
Single point turning	Kennametal K313 turning inserts	Direct aged Inconel 718	HRC 47-48	rake angel −5°; clearance angle 0°; setting angel 95°