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Structure, properties and wear performance of nano-multilayered TiAlCrSiYN/TiAlCrN coatings during machining of Ni-based aerospace superalloys

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ABSTRACT

New nano-multilayered TiAlCrSiYN/TiAlCrN coatings have been developed with various ratios of Ti/Al/Cr within Si + Y containing nano-layers.

The layered nanostructure of the coatings has been studied by STEM-HAADF mode and the nano-metric composition obtained by in-situ EDS. Micro-mechanical characteristics were investigated using a Micro Materials NanoTest System. Thermogravimetric-Differential Thermal Analysis (TG-DTA) was used within a temperature range of 25–1200 °C for oxidation resistance evaluation.

The wear performance of nano-multilayered TiAlCrSiYN/TiAlCrN coatings during machining of direct aged Inconel (DA) 718 and powder metallurgical ME 16 Ni-based superalloys has been investigated. The kinetic coefficient of friction under metal cutting conditions of Inconel was measured. The temperature range was 25–1000 °C.

It was shown that the composition of the nano-multilayered coatings and their characteristics have to be tuned for specific applications. A nano-multilayered coating with increased amount of Al (60 at.%) in Si + Y containing nano-layers that has strong oxidation resistance and a higher range of micro-mechanical properties related to crack propagation under scratch conditions behaves better during machining of Inconel DA 718 alloy. For machining of the more high temperature strong and thermally resistant ME 16 superalloy, a nano-multilayered coating with less Al (55 at.%) in Si + Y containing nano-layers that combines improved oxidation resistance with higher hardness and other beneficial micro-mechanical properties associated with resistance to plastic deformation performs best.

1. Introduction

Nickel-based superalloys are typically used in the manufacture of components for aerospace applications due to their unique combination of high strength at elevated temperatures in addition to strong chemical and thermal stability [1–3]. However these properties severely reduce the machinability of these alloys. Most problems encountered during machining are due to heat generation in the cutting zone and high friction at the tool–chip interface mainly due to intensive adhesive interaction with the workpiece. The austenitic matrix of Ni-based superalloys enables them to react with tool materials under atmospheric conditions and work harden rapidly. They have a tendency to adhere to the surface of cutting tools and form a built-up edge (BUE) [4,5], resulting in a non-stable attrition wear mode with severe surface damage [6]. Superalloys also contain abrasive carbide particles and as a result high wear rates of cutting tools are observed when machining these materials [7].

Recent improvements in aerospace alloys include new thermal–mechanical and powder metallurgical techniques for producing components with superior characteristics. For the aforementioned reasons high performance machining of these advanced Ni-based superalloys is a challenge. The introduction of superalloys such as Direct Aged Inconel 718 with improved strength [7] as well as powder metallurgical Ni-based superalloys such as ME 16 with further improved high temperature strength and reduced thermal conductivity makes their machining significantly more difficult [7,8]. The low thermal conductivity of these alloys leads to a significant increase in temperature of the cutting tools as less heat is removed from the tool-chip interface. The temperature range at the tool-chip interface can be as high as 900–1000 °C [1,2,6]. An approach to improve machining of

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these hard-to-cut materials is surface engineering of the cemented carbide cutting tools in particular by means of application of Physical Vapor Deposited (PVD) coatings. Various TiAlN, AlTiN and AlCrN-based hard PVD coatings are commonly used for this application [9–14]. A family of nano-crystalline TiAlCrN-based coatings [15] with (Si + Y) addition (around 5 at.%) has been recently developed for machining of hard to cut materials. The coatings have high hardness of 25–35 GPa depending on Al content and oxidation stability at elevated temperatures [16–18]. The roles Silicon (Si) and Yttrium (Y) are different within these coatings. The addition of Si results in grain refinement [19] and Yttrium addition to Si-content TiACrN coating prevents intensive grain coarsening at elevated temperatures [17]. Due to enhancement of the beneficial physicochemical reactions, protective alumina-based tribo-films are observed on the friction surface which reduce the wear rate [17]. This family of coatings shows promises for dry high-speed machining of hardened tool steels as well as machining of aerospace alloys [17,18].

Recently, nano-multilayer coatings have been reported to optimize and enhance coating properties and machining performance [19–29]. Various categories of multilayered coating have been studied that alternate nano-layers with different characteristics [30–36]. The coatings of special interest are nano-multilayered consisting of alternating nano-layers with a modulating chemical composition but similar crystal structure and hardness. It has been shown that it can be an efficient way to improve the coatings characteristics and enhance their wear performance [35].

The following hypothesis was made: introduction of the nano-multilayered TiAlCrSiYN/TiAlCrN coatings with modulating chemical composition but similar characteristics of the alternating nano-layers can be a way to improve properties of the TiAlCrSiYN-based coatings.

The goal of this paper is to perform an investigation of the structure, properties and wear performance of these newly developed nano-multilayered TiAlCrSiYN/TiAlCrN coatings during machining of various advanced Ni-based superalloys.

2. Experimental

Two nano-multilayered $Ti_{0.2}Al_{0.55}Cr_{0.2}Si_{0.03}Y_{0.02}N/Ti_{0.25}Al_{0.65}Cr_{0.1}N$ and $Ti_{0.15}Al_{0.6}Cr_{0.2}Si_{0.03}Y_{0.02}N/Ti_{0.25}Al_{0.65}Cr_{0.1}N$ coatings were deposited using $Ti_{0.2}Al_{0.55}Cr_{0.2}Si_{0.03}Y_{0.02}$; $Ti_{0.15}Al_{0.6}Cr_{0.2}Si_{0.03}Y_{0.02}N$ and $Ti_{0.25}Al_{0.65}Cr_{0.1}$ targets fabricated by a powdered metallurgical process. Mirror polished cemented carbide WC-Co substrates (SPG 422, SPGN 12 03 08) were selected for coating characterization and Kennametal K 313 inserts (CNGG432FS) were chosen for cutting tool life studies on a CNC lathe. Coatings were deposited in R&D-type hybrid PVD coater (Kobe Steel Ltd.) using a plasma-enhanced arc source. Samples were heated up to about 500 °C and cleaned through Ar ion etching process. $Ar–N_2$ mixture gas was fed to the chamber at a pressure of 2.7 Pa with a N_2 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; substrate rotation 5 rpm. The thickness of the coatings studied was around 3 µm for the film characterization and cutting test work.

Cross-sectional TEM observation was employed in combination with Focused Ion Beam (FIB) for investigation of the coatings on the cemented carbide WC/Co substrates. Transmission electron microscopy and selected area electron diffraction (SAED) were performed in a JEOL FS2200 microscope at an acceleration voltage of 200 kV. High annular angular dark field (HAADF) in scanning transmission electron microscopy mode (STEM) and EDX were employed to study the composition and elemental mapping. The micro-mechanical characteristics of the coatings were measured on WC-Co using a Micro Materials NanoTest system. Nanoindentation was performed in a load controlled mode with a Berkovich diamond indenter calibrated for load, displacement, frame compliance and indenter shape according to an ISO14577-4 procedure. The area function for the indenter was determined by indentations to 0.5–500 mN into a fused silica reference sample. For the nanoindentation of the coatings, the peak load was 40 mN and 40 indentations were performed for each coating. This load was chosen to minimize any influence of surface roughness on the data whilst ensuring that the indentation contact depth was under 1/10 film thickness so that a coating-only (load-invariant) hardness could be measured in combination with coating-dominated elastic modulus. Nanoindentation was performed at room temperature. Nano-impact testing was performed with a NanoTest fitted with a cube corner indenter as an impact probe. The indenter was accelerated from 12 µm above the coating surface with 25 mN coil force to produce an impact every 4 s for a total test duration of 600 s. The coatings' nano-impact fatigue fracture resistance was assessed by the final measured impact depth and confirmed by microscopic analysis of impact craters. Micro-wear (low cycling repetitive unidirectional sliding wear) tests were performed using the NanoTest Scratching Module with a 25 µm radius diamond probe. The 12-scan micro-wear procedure involved an initial topography scan followed by 10 scans where after a 200 µm leveling distance the load was ramped quickly (100 mN/s) to the peak load of 0.5, 1 or 2 N, and then followed by a subsequent topography scan. The scan speed was 5 µm/s and the total scan length was 800 µm. On-load and post-load, the probe penetration depth data in the constant load region (last 600 µm of each scan) was determined automatically after correction for the sample slope and frame compliance in the instrument software. Contact pressure was estimated during the scratch and wear tests. A Hertzian calculation was done to show that at 0.5 N, the maximum von Mises stress was at ~1.8 µm depth; by 1 N was at ~2.5 µm depth and by 2 N was at ~4 µm depth. Only by 2 N does this reach interface. At 0.5 or 1 N wear only occurs by isolated smoothing of asperities – almost completely elastic deformation – but at 2 N wear occurs on all films [37].

Oxidation resistance of the coating was studied by using Thermo-gravimetric-Differential Thermal Analysis (TG-DTA) within a temperature range of 25–1000 °C in air. This range of temperatures was selected to mimic the severe cutting conditions during machining of Ni-based superalloys. Temperatures at the tool/chip interface can reach 1000 °C [18]. To perform this test one side of the Platinum (Pt) foil (30 × 10 × 0.2 mm thick) was coated with 3 µm multilayered coating and subjected to the TGA measurement. Uncoated Pt was used as a reference sample during the test to measure the relative weight gain of the multilayered coating. The weight ratio of the Pt foil to the coating was is around 1:4.

The coefficient of friction vs. temperature was determined with the aid of a specially designed tribometer apparatus described in [38,39]. Three tests were performed for each coating to determine the

Table 1
Cutting data for the experiments performed.

Cutting data						
Machining operation	Cutting tool substrates	Workpiece material	Hardness	Speed, m/min	Feed, mm/rev	Depth of cut, mm
Turning	Kennametal K313 turning inserts	Direct aged Inconel 718	HRC 47-48	40	0.125	0.25
		ME 16	HRC 46-48	50		