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Multi-functional nano-multilayered AlTiN/Cu PVD coating for machining of Inconel 718 superalloy

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ABSTRACT

Machining of Ni-based aerospace alloys is one of the major challenges of modern manufacturing. Application of cemented carbide tooling with nano-multilayered AlTiN/Cu PVD coating results in a significant tool life improvement under conditions of turning the hard-to-machine aerospace Ni-based Inconel 718 superalloy. Studies of the structure, properties, tribological and wear performance of the nano-multilayered AlTiN/Cu PVD coating have been performed. The structure of the coating has been investigated using High Resolution Transmission Electron Microscopy. Various properties of the coating including microhardness, thermal conductivity and coefficient of friction vs. temperature were measured.
Investigations of the coated tool life, wear behavior and chip formation for cutting tools with nano-multilayered AlTiN/Cu PVD coating were performed. Morphology of the worn tools has been studied using SEM/EDX. AlTiN/Cu coatings present multi-functionality because they combine self-lubricating behavior with reduced thermal conductivity. This beneficial combination of properties results in significant improvement of the coated tool life.

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1. Introduction

Machining of Nickel-based aerospace superalloys is a challenge. Typical characteristics of Ni-based aerospace super-alloys include: high temperature strength and toughness, rapid work hardening, low thermal conductivity and a tendency to weld onto cutting tools and to form built-up edge (BUE) due to intensive adhesive interaction during friction under atmospheric conditions. Intensive adhesive interaction during cutting leads to significant heat generation [1]. This consequently results in intensive interaction with the environments such as oxidation attack. Due to these phenomena, diffusive and oxidation wear occur as well. An increase in high temperature strength of the workpiece material promotes deformation with consequent deep surface damage or even chipping of the cutting tool edge [2,37]. Attrition wear readily develops as a result of this interaction. The combination of all these factors has a pronounced adverse effect on tool life and results in extreme complexity of the wear behavior during cutting [1].

A way to improve machining of hard-to-cut materials is surface engineering of the cutting tools, in particular by means of application of Physical Vapor Deposited (PVD) coatings. To address these operating conditions, multi-functional coatings are typically needed. Nowadays, hard coatings for machining of hard-to-cut materials usually belong to the TiAlN family of coatings [3,4]. It was shown previously that aluminum-rich (up to 65 at.%) hard TiAlN are better suited for this application [5,6]. AlTiN-based coatings have a number of beneficial characteristics for machining of aerospace alloys. They are the following: a favorable combination of hardness that is able to sustain heavy loads under operation, increased plasticity and improved fatigue fracture resistance [7,8]. The other critical characteristic of the AlTiN-based coating is the ability to form protective alumina-like tribo-films during cutting due to high aluminum content and the nano-crystalline structure [9,10]. High thermal and chemical stability of the alumina tribo-layers prevents intensive sticking with the workpiece material during friction [10].

A major drawback of these coatings is a lack of lubricity. Thus, the coatings outlined above do not possess the necessary multi-functionality that is critically important for unstable conditions of attrition wear. This could be accomplished by deposition of multi-functional self-lubricating coatings [4]. One way to improve lubricity is the incorporation of a metal lubricant in the structure of the hard

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coatings [11]. Cu is a well known metal lubricant for machining of Ni-based superalloys [12]. Recently a number of various coatings, including multilayered TiN/Cu, TiAlN/Cu and CrN/Cu coatings were fabricated and their properties were investigated [13–20].

However, fundamental understanding of the microstructure, mechanical, physical, and tribological characteristics of such Cu containing multilayered coating is still lacking.

The goal of this paper is to determine the effect of Cu incorporation on the structure, properties, frictional and wear performance of nano-multilayered AlTiN/Cu coating during machining of Ni-based superalloys.

2. Experimental

An R&D-type hybrid coater (Kobe Steel Ltd.) was used in this study. An arc source (plasma-enhanced type [20] and an Unbalanced Magnetron (UBM) sputtering source were installed in a counter-facing manner. Various substrates were used for the coating deposition such as: mirror polished WC–Co cutting inserts for micro-mechanical properties measurements and SPG 422 turning inserts (Sandvik) for tool life studies. An $Al_{0.67}Ti_{0.33}$ target manufactured by a powder metallurgical process was used as the arc cathode, while a Cu metallic target was used as the sputtering source. Details of our deposition technique for nano-multilayered coatings are published elsewhere [21,22].

XRD studies of the coatings under analysis have been performed to identify the phases formed using a Siemens D500 diffractometer with a Cu K_{α} tube and the $\Theta/2\Theta$ mode.

Cross-sectional TEM was employed in combination with FIB (focused ion beam) 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)-STEM image of the coating was employed with EDX profile of the coating layer. The diameter of the electron-beam probe was 1 nm.

EDX linescan was performed by a special JEOL EDS detector. This prototype detector contained a 50 mm^2 area which increases the solid angle of detection. The result is an increased signal intensity with strong precision in quantifying light elements (C, O, and N). The analysis was performed along the 100 nm long line, within 2 nm step. The beam diameter in the STEM mode was 1 nm.

Thermal conductivity was measured by picosecond time-domain thermoreflectance (TDTR). TDTR is a pump-probe optical metrology that uses an ultrafast laser oscillator as the light source [23]. The data acquired in the measurement are analyzed using a numerical solution of the diffusion equation for an arbitrary layered structure [24]. For these measurements, the specific parameters were: 1) laser $1/e^2$ spot radius of 16 µm, 2) total laser power incident on the sample of 16 mW, 3) pump modulation frequency of 9.8 MHz, 4) transducer is a sputtered Cr film of 100 nm thickness and 5) temperature measurement using a Pt RTD attached to the surface of the sample by Ag paste. Electrical resistivity of AlTiN coating was measured by the Kelvin Probe method. Samples used for electrical resistivity measurements were deposited on glass substrates.

For the calculation of thermal conductance, (see below 'Discussion' section) evaluation of volume fraction of Cu phase in AlTiN/Cu nano-multilayered coating was made. The volumetric fraction, for the AlTiN/Cu coating composition shown in Table 2 was calculated assuming the coating is a mixture of (AlTi)N and Cu. The compositional ratio of N and Cu was easily measured using EDX analysis (Table 2) as N and Cu are chemically inert with respect to each other. As a result, once the number of moles of Cu and N are known, the relative number of moles of (AlTi) is known as (AlTi) is 1:1 with respect to N in the compound (AlTi)N. This then leads to the volumetric ratio of AlTiN and Cu.

Coatings were also subjected to compositional (EDX), structural (SEM) and mechanical (micro-indentation) analysis [25]. Nano-indentation 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 using a nano-indentation instrument (Elionix ENT-1100). The area function for the indenter was determined by indentations to 0.5–500 mN into a fused silica reference sample. For the nano-indentation into the coatings, the peak load was 20 mN and 25 indentations were performed for each coating. This load was chosen to minimize any influence of surface roughness while ensuring that the indentation contact depth was under 1/10 the film thickness so that a coating-only (load-invariant) hardness could be

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	CC indexable inserts SPG 422	Inconel 718	HRC 47–48	40	0.125	0.25

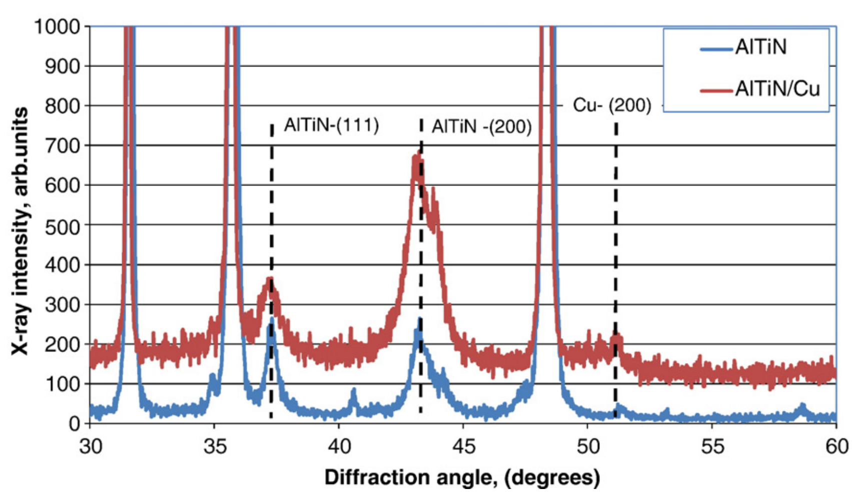

Fig. 1. XRD data on AlTiN mono-layered and AlTi/Cu nano-multilayered PVD coatings.

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