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Nanolayered CrAlTiN and multilayered CrAlTiN–AlTiN coatings for solid particle erosion protection

Q. Yang*, R. McKellar

Structures, Materials and Manufacturing Laboratory, Aerospace Portfolio, National Research Council Canada, 1200 Montreal Road, Ottawa, ON, Canada K1A 0R6

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ABSTRACT

Applying hard coatings on airfoil surfaces is proven to be an effective approach to mitigating erosion damage to engine components. Nanolayered or multilayered coatings, because of their capability of tailoring hardness and toughness through modifications in the chemistry and architecture of layer constituents, have been explored as potential candidates for this specific application. In this study, nanolayered CrAlTiN (CrN/AlTiN) coatings with different modulation periods, along with multilayered CrAlTiN–AlTiN coatings having different number of layers and different thickness of individual layers, were fabricated, characterized and evaluated. All the coatings significantly outperformed the CrN baseline in erosion resistance, and their performance was strongly affected by the bilayer period of the nanolayered coatings or the layer architectural characteristics of multilayered coatings.

1. Introduction

Aircraft engines operating in a sandy environment [1], because of sand particle ingestion, are subject to severe erosion damage to compressor blades, vanes, or impellor blisks/wheels. The damage can appear on those components as pitting and cutting back of the leading edge, thinning of the trailing edge and blade chord shortening [2–4]. The physical change in blade geometry due to erosion affects the dynamic response characteristics of compressor airfoils [5,6], and consequently causes an increase in fuel consumption and life reduction of the hot section of the engine [7]. As erosion progresses, a significant amount of material removal not only leads to further aerodynamic losses, but results in the structural weakening of blades as well. When the damage becomes excessive, component integrity and aircraft safety are compromised. Early removal of some helicopters from field operations has been reported due to excessive erosion of compressor blades [8]. Replacement of the parts whose erosion damage limits have been reached is costly, and can cause logistic issue of engine availability.

There are several approaches to minimizing erosion damage in gas turbine engines, including using filtration of inlet air, improving engine design, optimizing the intake positioning, and applying erosion resistant coatings over component surfaces [9–11]. Monolithic transition metal nitride coatings, such as TiN [12,13], CrN [14,15], TiAlN [16] and TiSiN [17], have been investigated as erosion resistant coatings for engine components. TiN coating was first implemented by Russia during its military involvement in Afghanistan where sand erosion seriously limited the life of helicopter turbine engines. Though it provided excellent protection to compressor blades from erosion at low sand impingement angles [18], it is susceptible to fracture and spalling from substrate due to its brittleness, especially when being impacted at high angles by high speed particles [19]. CrN coating, which has toughness higher than TiN [20], is unfavorable as a candidate for erosion resistant application since it is not hard enough to effectively resist materials removal by particles through micro-cutting.

Generally speaking, coatings having high hardness and toughness can withstand impact loading and resist crack formation [21], resulting in excellent resistance against solid particle erosion. Whereas such a combination of mechanical properties is usually difficult for monolithic binary transition metal nitrides to achieve, it can be realized through incorporating alloying elements, modifying coating microstructures and architectures, or using a combination of these two. Coatings with a multi-layered structure can potentially be harder and significantly tougher than homogeneous coatings of the same materials [22,23] since the layered structure obstructs dislocation glide and crack propagation [24–26]. Toughening by a multi-layered architecture is attributed to the effects of interfaces on dissipating crack energy and deflecting cracks [25–27]. Nanolayered coatings, which consist of nanometer-scale multilayers of alternating materials with a modulation period in the range of several to a hundred nanometers, are also promising in achieving high hardness [28,29] and improving toughness due to interface toughening [30–32]. Therefore, it is not surprising that

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* Corresponding author. Tel.: +1 613 9934335.
E-mail address: qi.yang@nrc-cnrc.gc.ca (Q. Yang).

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improved erosion performance has been reported for some nanolayered [17,33,34] and multilayered coating systems [35,36].

Though nanolayered CrAlTiN coatings have been demonstrated high hardness and excellent dry drilling/milling performance [37,38], their sand particle erosion performance has not yet been investigated. In this study, nanolayered CrAlTiN (CrN/AlTiN) and multilayered CrAlTiN–AlTiN coatings were explored as erosion protective coatings. As the mechanical properties of nanolayered and multilayered coatings are microstructural dependent [27,39], the microstructural effects on erosion performance needs to be investigated. Therefore, two nanolayered CrAlTiN (CrN/AlTiN) coatings with different modulation periods, along with four multilayered CrAlTiN–AlTiN coatings having different number of layers and different thickness of individual layers, were fabricated, characterized and evaluated for their solid particle erosion resistance.

2. Experimentals

The Metaplas Ionon MZR-304 cathodic arc coater, was used for coating deposition. The cathodes were mounted on two flanges, with Cr cathodes installed vertically on one flange and Al67Ti33 cathodes on another. An electrical heater and an arc enhanced glow discharge (AEGD) cathode were mounted at opposite locations between the flanges. 17-4PH stainless steel flat coupons of 50 mm in diameter were mechanically ground and polished to a mirror polished surface finish. Prior to coating deposition, the samples were ultrasonically cleaned in acetone and in alcohol, and then dried with warm air. The coupons, as substrate for coating deposition, were then placed in the fixtures on a dual-axial rotation table. The deposition process was executed in three consecutive stages: pumping, AEGD cleaning and coating deposition. First, the chamber was pumped down with the electrical heater on to accelerate the removal of moisture from the chamber. After the desired vacuum was achieved, the coupons were AEGD ion-cleaned using one Ti evaporator with a fixed shutter in front of it; Ar ions were attracted by negatively biased specimens to provide ion surface cleaning. An AEGD anode current of 80 A and a substrate bias of −280 V were applied for 30 min to effectively ion-clean the substrate material.

A mixture of Ar and N_2 gases was used for coating deposition. N_2 gas was utilized to form nitride coatings with evaporated cathode materials while Ar gas with a constant flow rate helped to achieve a working pressure of 5 Pa. A bias voltage of −40 V was applied on the substrate for energetic ion bombardment on the growing coating. A table rotation speed of 2 rpm was kept throughout the whole deposition process, except for one run with a rotation speed of 4 rpm for depositing one of the nanolayered CrAlTiN coatings. The total coating thickness was controlled by the total ampere-hour (Ah), which was set to 1500 Ah for all the coating deposition runs. Two nanolayered CrAlTiN coating systems with different bilayer periods were deposited by applying two different table rotation speeds (2 rpm and 4 rpm). The multilayered coatings, with AlTiN as the first layer to be deposited, were produced by periodically turning the Al67Ti33 cathodes on and off. The ratio of Ah values between individual CrAlTiN and AlTiN layers was set to ~2.3 to produce multilayered coatings with similar thickness ratio between CrAlTiN and AlTiN layers. Four multilayered coatings were deposited with different numbers of alternating layers. The Ah numbers for the individual layers of these coatings are listed in Table 1. Monolithic CrN coating, as a baseline for sand particle erosion performance, was also produced.

The as-deposited coating surfaces and cross-sections, and eroded coating surfaces were examined using a Philips XL30 field emission scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS). X-ray diffraction (XRD) analyses were performed to characterize coating crystallographic structures, using a Bruker AXS D8 Discover diffractometer with a Co $K\alpha$ radiation ($\lambda = 1.790$ Å) at 40 kV and 35 mA. The diffraction spectra were generated in a step-scan mode, with a step size of 0.021° and a step time of 0.87 s. The hardness of the nanolayered CrAlTiN coatings and monolithic CrN were determined on the coatings' cross-sections using CSEM nanohardness tester with a Berkovich indenter and a load of 50 mN; but no hardness measurements were performed on the multilayered coatings due the thin nature of each constituent layers.

Erosion tests were conducted at room temperature following the ASTM standard G76-04 [40], using an S. S. White Industrial Airbrasive Unit, model HME. Angular alumina (Al_2O_3) powder with an average size of 50 µm (Fig. 1), placed into a pressurized vibrator-controlled hopper, was introduced into a N_2 gas stream, which carried the particles through a silicon carbide nozzle with an inner diameter of 1.14 mm (0.045 in.). The particle-N_2 gas stream was directed towards the testing coupon at a preset impingement angle. The velocity of the particles was controlled by adjusting the pressure of the N_2 gas, and the particle flux (feed rate) was regulated by changing the vibrating amplitude of the hopper. During testing, the coupon surface to nozzle tip distance was maintained constant at 38 ± 1 mm. The coatings were tested at impingement angles of 30º and 90º, with a particle velocity of 84 m/s (300 km/h) and a particle feed rate of ~1 g/min. The test was terminated once the tested coating was perforated. The weight loss of tested coupons, which were measured using a precision balance with an accuracy of 10^{-5} g, was used to calculate the mass erosion rate—the weight loss per gram of erodent.

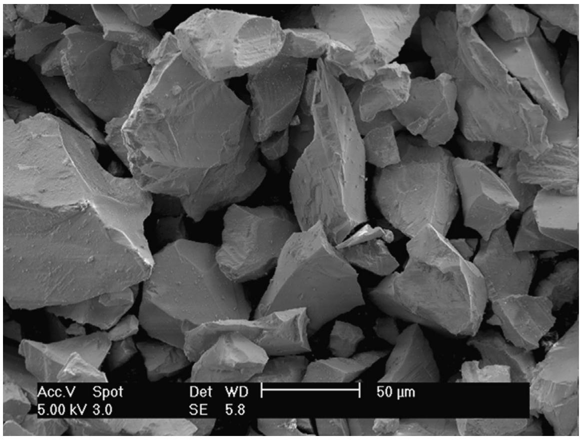

Fig. 1. Sharp edged Al_2O_3 particles used for erosion testing.

Table 1
Layer numbers and Ampere*hour (Ah) values for CrAlTiN–AlTiN multilayered coatings.

Coating		CrAlTiN–AlTiN (6–6)	CrAlTiN–AlTiN (10–10)	CrAlTiN–AlTiN (15–15)	CrAlTiN–AlTiN (19–19)
CrAlTiN layers	Layer number	6	10	15	19
	Ah per layer	175	105	70	53
AlTiN layers	Layer number	6	10	15	19
	Ah per layer	75	45	30	22