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Enhancing the tribo-mechanical properties of aerospace AL7075-T6 by magnetron-sputtered Ti/TiN, Cr/CrN & TiCr/TiCrN thin film ceramic coatings

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Abstract

Binary (Ti/TiN and Cr/CrN) and ternary (TiCr/TiCrN) thin films were deposited on AL7075-T6 by magnetron sputtering. Microhardness, adhesion strength and pin-on-plate wear tests were performed to investigate coating performance. Field emission scanning electron microscope integrated with focused ion beam milling and energy dispersive X-ray spectroscopy was employed for microstructural and chemical characterizations. The tribo-mechanical test results revealed that Cr/CrN promoted up to 5 times greater hardness, Ti/TiN showed the highest scratch resistance and up to 8 times reduced wear, while TiCr/TiCrN favored the least friction and surface roughness. Furthermore, the excellent tribological properties of coatings correlated with their superior adhesion to AL7075-T6.

Keywords: Ceramic coatings; Magnetron sputtering; AL 7075-T6 alloy; Tribo-mechanical properties

1. Introduction

The use of aluminum alloys in the automotive and aerospace industries has become pervasive due to their distinctive properties in contrast to ferrous alloys [1]. With the advancements in manufacturing various aluminum alloys such as AL 7075-T6, unprecedented properties like high strength-to-weight ratio, fatigue strength, fretting fatigue life, and fracture toughness have resulted in lightweight failure-resistant components [2]. Applications of AL 7075-T6 include aircraft fittings, gears and shafts, regulating valve parts, worm gears, keys, and fastened joints, where fretting fatigue damage like fretting wear can pose catastrophic failure under cyclic loading [3,4]. Baydoğan et al. and Cai Zhen-bing et al. reported that under dry sliding wear, AL 7075-T6 undergoes severe wear susceptibility due to its relatively low surface hardness and high ductility. Many efforts including modifications to bulk and surface properties have been made, such as PACVD [5] and thermal spraying [6] coating techniques, which expose the substrate material to high temperatures during the coating process and degrade it.

Apart from the afore-stated coating techniques, low temperature deposition methods such as physical vapor deposition are effective in developing hard and wear-resistant surfaces, mainly due to having better step coverage, availability of a wide range of target materials, uniform coatings over larger areas and minimal shadow effects [7].

Thermal evaporation, ion plating and magnetron sputtering are some of the common PVD methods, but thermal evaporation and ion plating techniques result in poor coating adhesion and may require complex evaporative compositions to preserve stoichiometry besides posing complicated process control. Magnetron sputtering technology permits the deposition of complex, uniform and dense coatings at lower temperatures with higher adhesion to substrates besides preventing hardness reduction, which results in enhanced tribo-mechanical performance [8,9].

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Binary transition metal nitride coatings, among which titanium nitride and chromium nitride, supplement coatings by contributing superior mechanical properties [10–14]. Chromium nitride coatings have interesting properties like high hardness, good coating-to-substrate adhesion and low wear, which render them superior over titanium-based coatings that are inherently more brittle [15–18]. For instance, CrN has been used in tools made of relatively softer substrates such as stainless steel, copper and aluminum alloys that cannot provide rigid support for the more brittle coatings [19]. In contrast, properties furnished by binary coatings are now insufficient. Various comparisons have been made between TiN and CrN, but no investigations have been carried out on combining these phases into one single film coated onto AL 7075-T6 using magnetron sputtering technique. Nainaparampil et al. reported that the friction coefficient for (Ti–Cr)N deposited on M-50 steel by cathodic arc process, is lower than the friction coefficients of TiN and CrN in their original states [20]. Besides, titanium chromium nitride coated on stainless steel AM355 exhibited improved tribological performance [21]. Therefore, titanium chromium nitride presents a realistic solution, as it hinders the damage mechanisms that degrade bulk material properties.

In the current research, the aim is to obtain coating parameters for magnetron sputtering that result in higher hardness and adhesion strength, and to evaluate the enhancement of tribo-mechanical aspects of PVD binary (Ti/TiN, Cr/CrN) and ternary (TiCr/TiCrN) thin ceramic films deposited on high-strength AL 7075-T6.

2. Experimental details

2.1. Material and sample preparation

Round bar samples of AL 7075-T6 were cut in dimensions of 20 mm diameter and 5 mm thickness using electro-discharge wire cutting (EDWC). The samples were ground with 800 to 2200 grit SiC grinding paper and mirror polished with polycrystalline suspended diamond liquid (Buehler). The samples were subsequently degreased and cleaned in acetone with ultrasonic equipment for 15 min, thereafter thoroughly rinsed with distilled water and dried using nitrogen gas to avoid surface contamination before coating. The chemical composition of AL 7075-T6 substrate (in wt%) is 4.6 Zn, 1.8 Mg, 1.85 Cu, 0.06 Mn, 0.47 Si, and 0.28 Cr. Pure titanium and chromium targets with purity of 99.9955% and 99.95% respectively, were utilized to deposit the binary and ternary thin film nitride coatings on the substrates.

2.2. Binary and ternary coatings procedure

"SG Control Engineering Pte Ltd" magnetron sputtering equipment with a circular and rotatable substrate carrier at various speeds was used to deposit multilayered thin films of Ti/TiN, Cr/CrN and TiCr/TiCrN on AL 7075-T6 substrates. It is worth mentioning that multilayer coatings have the good adhesion strength as an advantage due to the presence of an interlayer that covers substrate defects, provides a smoother surface and acts as a residual stress reducer. The magnetron sputtering system comprised 600 W RF and 1200 W DC generators with $4\times12''$ electrodes placed 15 cm away from the targets. In order to sputter the metals with ease, DC generators were designed. In case of binary Ti/TiN and Cr/CrN, the pure Ti and Cr targets were deposited separately, whereas for TiCr/TiCrN, the metal targets were deposited simultaneously. The deposition chamber was initially evacuated to less than 2×10^{-5} Torr before argon gas was introduced for sputtering, and it was increased to a constant sputtering pressure of 5.21×10^{-3} Torr for the deposition process. In the last step, namely ion-etching or Ar+ sputtering, the ions were accelerated by applying substrate bias potential onto the substrate. In the ion-etching process, oxides or chemisorbed nitrogen and carbon atoms were removed. The deposition durations for the first, interfacial layers (pure titanium, chromium and titanium/chromium) and the second layers (titanium nitride, chromium nitride and titanium chromium nitride) were adjusted to 1.5 and 3 h, respectively. The parameters affecting deposition rate were DC power, temperature and nitrogen flow rate. In this experimental work, sixteen experiments were carried out for each type of coating in order to get a wide range of results. The parameters and levels along with the experimental design for Ti/TiN, Cr/CrN and TiCr/TiCrN coatings are shown in Tables 1 and 2 respectively.

Table 1
Parameters and levels used in the experimental design.

Parameters		Levels			
		1	2	3	4
A	DC power (W)	200	300	400	500
B	Temperature (°C)	150	200	250	300
C	Nitrogen flow rate (%)	3	6	9	12

Table 2
Standard L_{16} (3^4) orthogonal array experimental design for Ti/TiN, Cr/CrN and TiCr/TiCrN coatings.

Experiment	**Control factors and levels**		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

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