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The effect of deposition parameters on the mechanical properties of Cr–C–N coatings

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ABSTRACT

Cr–C–N coatings were deposited on a high-speed tool steel and Si wafer in $Ar/N_2/C_2H_2$ plasma with various fixed target currents (1–5 A) using a reactive magnetron sputtering process. This study investigates the effect of the target current on the coating structure and the mechanical properties of the Cr–C–N coatings. Experimental results indicate that the target current (TC) clearly affects the coating structure and mechanical properties. X-ray diffraction results show that the Cr–C–N coating structure can be separated into two categories. The Cr–C–N coatings with a TC less than 2 A exhibit an amorphous DLC structure, while the Cr–C–N coatings with a TC greater than 3 A exhibit a crystalline structure. The Cr–C–N coatings with an amorphous DLC structure exhibit a lower friction coefficient, while the Cr–C–N coatings with a crystalline structure exhibit a higher friction coefficient. The Cr–C–N coatings with a lower friction coefficient exhibit a lower wear rate.

1. Introduction

Physical vapor deposition (PVD) processes have long been widely used in the preparation of hard coatings due to their superior combined properties, such as high hardness and good resistance to wear [1,2]. Chromium nitride (Cr–N) is usually used for hard protective coatings because of their good wear and corrosion resistance [3–6]. However, the wear resistance of conventional Cr–N coatings is quite limited. Adding metal elements into nitride to form ternary thin films produces higher hardness and wear resistance [7]. The incorporation of Al or Si to chromium nitride results in higher hardness, as well as greater thermal and chemical stability [8].

The addition of carbon into chromium nitride has an important effect on the microstructure and properties of the coatings. The sputtering current of the targets and flow rate ratio of hydrocarbon gasses are the main parameters affecting the C content in Cr–C–N coatings. The incorporation of C into Cr–N results in increased hardness and wear resistance, and a lower friction coefficient [9–12]. The friction coefficient and wear rate of Cr–C–N coatings depend on their carbon content [13].

Previous research has focused on the effect of the N_2 or C_2H_2 flow rate ratio on tribological properties of Cr–C–N coatings [9,13]. However, little attention has been focused on the effect of target current (TC) on tribological properties and crystal structures. In this study, the ternary system Cr–C–N was deposited in $Ar/N_2/C_2H_2$ plasma with two chromium targets. The Cr–C–N coatings were deposited using various TC levels to explore the effect of TC on crystal structures and wear resistance. The relationship between crystal structures and tribological behavior were investigated.

2. Experimental details

2.1. Coating preparation

The Cr–C–N coatings were deposited on the JIS SKH51 high speed tool steel and Si wafer in $Ar/N_2/C_2H_2$ plasma with two chromium targets using a reactive magnetron sputtering process. The deposition chamber measured 550 mm in diameter and 500 mm in height, while the dimensions of the target were 300 mm × 109 mm × 10 mm. The purity of the Cr, Al target materials was 99.5%, and the gas purity of the Ar, N_2 and C_2H_2 was 99.999%. The high speed tool steel and Si (100) substrates were cleaned in an ultrasonic cleaner with surfactants for 15 min, then with de-ionized water for 10 min, and then dried at 100 °C for 15 min before the coating deposition. Prior to deposition, the coating chamber was pumped down to 2.6×10^{-3} Pa. Substrates were bombarded using argon ion (Ar^+) at a pressure 0.57 Pa and a bias of −400 V for 20 min before deposition. The thickness of all specimens was controlled at 2.0 ± 0.1 μm by controlling the deposition time. The Cr–C–N coatings were deposited with various TC levels. The deposition temperature of all coatings was about 200 ± 20 °C. All deposition parameters are shown in Table 1.

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Table 1
Deposition parameters for Cr–C–N coatings.

Interlayer Cr	
Target material	Cr
Total flow rate (Ar) (sccm)	30
Working pressure (Pa)	0.40
Target sputtering current (A)	3
Substrate bias frequency (kHz)	50
Bias of substrate (−V)	70
Thickness (nm)	180
Cr–C–N coatings	
Target material	Cr
Flow rate (Ar) (sccm)	25
Flow rate (N_2 + C_2H_2) (sccm)	25
Flow rate ratio C_2H_2/(N_2 + C_2H_2) (%)	80
Working pressure (Pa)	0.40
Target sputtering current (A)	1, 2, 3, 4, 5
Substrate bias frequency (kHz)	70
Bias of substrate (−V)	75
Duty cycle (%)	15
Target to specimen distance (cm)	9

2.2. Coating characterization

The crystal structure of the coatings was characterized by grazing incidence X-ray diffractometer (Bede, D1 HR-XRD) with Cu Kα radiation (λ = 1.5418 Å). The scanning speed was set at 3° (2θ/min). Thicknesses and morphologies were observed by field-emission scanning electron microscopy (FE-SEM, JEOL JSM-6700F) with an accelerating voltage of 10 Kv. Chemical compositions were measured using energy dispersive spectroscopy (EDS) during the SEM investigation. The sliding wear behavior of the coatings deposited on the high-speed steel specimens was investigated by means of a ball-on-disk wear testing machine (Freeform, SMT1-25N) with a 6.3 mm diameter Cr steel ball (C: 0.95–1.10%, Cr: 1.30–1.60%, Si: 0.15–0.35%, hardness of 62–65 HRc). The sliding velocity was set at a constant speed of 0.3 ms^{-1}. The rotation cycle diameter, sliding distance and normal load were respectively set at 10 mm, 1000 m and 5 N. The wear rate was observed using a 3D scanning system (TalyScan 150) and a mathematical estimation model [14]. Microstructures were observed using transmission electron microscopy (TEM, FEI Tecnai G2 F20 S-Twin) and X-ray diffraction (XRD, Cu Kα, PANalytical X'pert PRO). The crystal structure of the selected coatings was characterized using a micro-Raman system (HORIBA Jobin Yvon, HR-800) with a backscattering configuration and a 100× optical microscope objective. The micro-hardness of the Cr–C–N coatings were characterized using a Vickers micro-hardness tester (FUTURE-TECH, FM-700) with load of 10 gf and calibrated using a model proposed by Jönsson and Hongmark [15]. The adhesion strength was characterized using a scratch tester (Freeform, FM-POD-200NT) equipped with a diamond stylus (tip radius 200 mm and cone apex angle 120°). Scratches were performed under a linearly increasing load of 100 N min^{-1} and a maximum normal load of 100 N. The scratch length and horizontal speed was respectively 10 mm and 10 mm min^{-1}.

3. Results and discussion

3.1. Wear and friction behavior

The wear behavior of the coatings was investigated using a ball-on-disk wear testing machine. According to the wear results, the TC clearly affects the wear behavior. Fig. 1 shows the friction curves of the Cr–C–N coatings with various TC levels. In Fig. 1 the friction coefficient can be separated into two categories. The lower friction coefficient category corresponds to a TC less than 2 A while a TC greater than 3 A shows a higher friction coefficient.

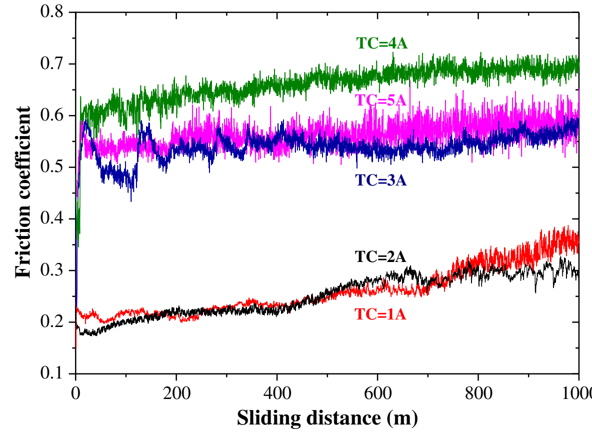

Fig. 1. Friction curves of the Cr–C–N coatings with various TC levels.

Fig. 2 shows the typical wear track depth profile of the Cr–C–N coating with TC of 2 A and 4 A. The profile indicates that the Cr–C–N coating with a TC of 4 A reveals a broader wear track. The coating with a TC of 2 A is only partially removed and exhibits a smoother track surface. According to the wear tracks, the wear rates of coatings were calculated. Fig. 3 shows the wear rate and friction coefficient of the Cr–C–N with various TC levels. The coating with a lower TC of 2 A shows the lowest friction coefficient of 0.25 and the lowest wear rate of 4.2 × 10^{-6} mm^3 N^{-1} m^{-1}. As the TC increases to 3 A, both the friction coefficient and wear rate clearly increase. The coatings with a TC greater than 3 A exhibit a higher friction coefficient and wear rate. According to Figs. 1 and 3, both the coatings with a TC greater than 3 A exhibit similar friction curves, wear rates and friction coefficients. Based on the

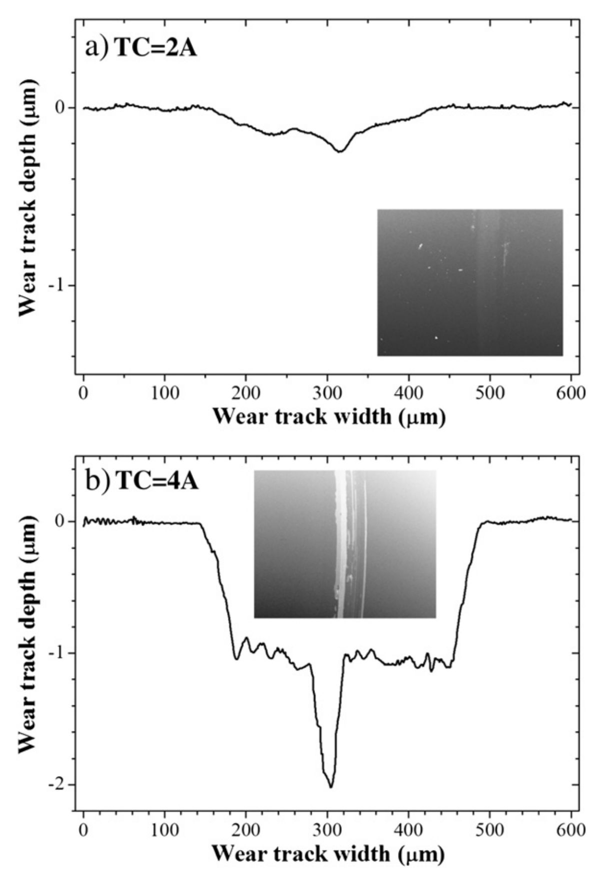

Fig. 2. Wear track depth profile of the Cr–C–N coating with TC of (a) 2 A and (b) 4 A.