Improving Tribological Properties and Machining Performance of a-C Coatings by Doping with Titanium

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1. Introduction

Amorphous carbon (also known as diamond-like carbon or DLC) can be classified as either hydrogen-free amorphous carbon (a-C) or hydrogenated amorphous carbon (a-C:H). DLC is an ideal surface coating material because it possesses high hardness, good chemical resistance, and excellent tribological properties (Ref 1-13). a-C films have attracted considerable attention in the tribological and semiconductor fields because they possess exceptional properties, including good corrosion resistance, high wear resistance, low friction characteristics, high hardness, high electrical resistivity, high thermal conductivity, high dielectric strength, and good infrared (IR) optical transparency. The favorable properties of a-C coatings have led to their widespread application throughout the engineering, electronic, optical, and biological fields (Ref 14-17). Many researchers have investigated the basic physical, mechanical, and tribological properties of a-C and have attempted to further improve its adhesive and tribological properties by developing so-called a-C:Me films, in which the a-C film is doped with additional metal materials (Ref 18-22). The tribological behavior of a-C:Me coatings is dependent on their composition and structure. The a-C:Me coating that provides the optimal performance in one particular application is not necessarily the most appropriate coating for another application. Therefore, it is essential that the tribological behavior of a-C:Me coatings under different operating conditions be fully understood.

Using a medium-frequency twin magnetron sputtering and unbalanced magnetron sputtering system, this study deposits a-C:Ti\(_{10\%}\) coatings with various levels of Ti addition on cemented tungsten carbide (WC-Co) disks, turning cutters, and microdrills. The coated turning cutters are tested against AISI 1045 steel counterbodies and the microdrills used in the high-speed through-drilling of printed circuit board (PCB) workpieces to establish the optimal a-C:Ti\(_{10\%}\) coating for each application.

2. Experimental Details

2.1 Specimen Preparation

The cylinders used as the upper specimens (counterbodies) in the wear tester were AISI 1045 steel (\(H_t\), 286, 50 g), cut off directly from round as-purchased stock and then mechanically polished to a roughness of \(R_a = 0.32 \mu m\). Meanwhile, the lower specimens, used as the coating substrates, were cemented WC-Co disks, whose surfaces were mechanically polished to \(R_a = 0.008 \mu m\). After machining the disk and cylinder specimens to the exact dimensions required to fit the wear tester apparatus, the specimens were ultrasonically cleaned in acetone and then stored in an electric dryer to protect their surfaces from recontamination.

2.2 Tribology Tests

The tribological properties of the various coatings were evaluated using a Schwingung Reibung Verschleiß (SRV) oscillation friction and wear tester (Optimol Instruments Prüftechnik GmbH, Munich, Germany). Figure 1 presents a schematic diagram of the experimental setup and indicates the dimensions of the upper and lower test specimens. The arrangement of a cylinder mating with a disk forms the cylinder-on-disk line contact wear mode. The wear tests were performed at room temperature under atmospheric pressure. The relative
humidity of the laboratory was 45-55%. Each coating was wear tested for 24 min. For each coating, two wear tests were performed, using new disks and cylinders in each test. After each wear test, the maximum depth of the wear scars on the lower disk was established using a surface profilometer (Surfcorder SE-30H, Kosaka Laboratory Ltd, Tokyo, Japan) with a precision of ±0.05 μm at a magnification of 2 × 10⁴. Three depth measurements were taken from each tested disk. A total of six maximum wear depth measurements obtained for each coating were then averaged to give an overall wear depth for the coating.

2.3 Machining Tests

2.3.1 Turning Test. In the turning tests, an indexable WC turning cutter (catalog No. TNMA160404 Ht10, Mitsubishi, Japan) of grade ISO K10 was used to machine AISI 1045 bar steel. The turning cutter had a triangular geometry with sides of 12 mm and a thickness of 5 mm. The machining performance of the turning cutter was evaluated by measuring the flank wear on the cutting edge. The turning tests were performed on a traditional lathe (catalog No. TSW-70K, TaShi, Taiwan) under the following operating conditions: rotation speed, 275 rpm; depth of cut, 2.0 mm; feed rate, 0.066 mm/rev; and duration, 27.5 min. Two turning tests were performed for each coated cutter, and three flank wear measurements were obtained in each test. The overall flank wear measurement for each coated cutter was taken as the average of the six individual flank wear measurements.

2.3.2 Drilling Test. To investigate the feasibility of applying the coatings to industrial machining applications, the coatings showing better wear resistance in the turning tests were deposited on microdrills and used in a series of drilling tests. Using a commercial machining center (Prosys1, Anderson, Taiwan), high-speed through-hole drilling tests were performed on PCB substrates to assess the machining performance of the various coated microdrills. The drilling tests were performed using WC microdrills (RH-RDS, Tungaloy, Taiwan) with the following geometrical configuration: diameter, 0.3 mm; overall length, 38.1 mm; fluted length, 5.4 mm; helix angle, 35°; and point angle, 135°. The PCB boards measured 120 × 120 × 1.6 mm and were formed of glass fibers embedded in epoxy resin. The boards were coated on either side with a copper layer 35 μm thick. Drilling was performed at a rotation speed of 100,000 rpm and a feed rate of 6.8 m/min. For each coating, five microdrills were prepared and tested. Machining performance of each coated microdrill was evaluated with an optical measurement system to measure the corner wear of the cutting edge after the drilling of 1000, 5000, 10,000, 15,000, and 20,000 holes, respectively, under dry conditions. The wear value of each coating was then established by calculating the average of the five individual wear test measurements.

2.4 Coating Deposition

The present coatings were deposited using the Genco Twin lab system (GENCOA Ltd., Liverpool, UK). This system comprised a medium-frequency twin balanced magnetron sputtering system and an unbalanced magnetron sputtering system. Each system had two targets, namely, titanium and carbon targets in the unbalanced magnetron sputtering system and two carbon targets in the balanced magnetron system. Prior to deposition, the substrates were sputter-cleaned by Ar⁺ bombardment for 10 min at a bias of −350 V. A 0.1 μm Ti interlayer was then deposited on each substrate to improve the adhesion of the coatings. During the deposition process, both systems were operated simultaneously and the balanced magnetron sputtering system was connected to an oscillator to generate a magnetic field alternating at a medium frequency of 800 Hz. The distance between the substrates and the targets was 10 cm. The percentage addition of Ti metal in each a-C:Tiₓ⁺ coating was varied by adjusting the magnitude of the current applied to the Ti target. The coatings were all grown for the same deposition time. Other than the Ti target current, which varied from coating to coating, the other deposition parameters remained constant for all of the coatings, i.e., total chamber pressure, 1.5 × 10⁻⁴ torr; substrate temperature, 200 °C; carbon target power, 2 kW; and bias voltage, −55 V. As shown in Table 1, a total of 10 different coatings were produced (T0-T9).

2.5 Observation and Analysis Equipment

The wear surfaces and cross sections of the coatings were observed using scanning electron microscopy (SEM) and x-ray mapping (energy dispersive spectrometer [EDS]). The elemental compositions of each coating were analyzed using glow discharge optical emission spectroscopy (GDOES).

3. Results

3.1 Coating Structure and Basic Mechanical Properties

3.1.1 Composition. Table 1 presents the Ti and C compositions of each a-C:Tiₓ⁺ coating. The x% value of the various coatings indicates the atomic percentage of Ti metal, and ranges from 0 to 51%. Table 1 shows that the coating thickness increases with increasing Ti concentration (i.e., with increasing titanium target current).

3.1.2 Microstructure. The microstructure of the a-C:Tiₓ⁺ coatings varies with the level of Ti addition. Figure 2(a) to (c) presents typical scanning electron photomicrographs of the