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Dry machining of metal using an engraving cutter coated with a droplet-free ta-C film prepared via a T-shape filtered arc deposition

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ABSTRACT

Tetrahedral amorphous carbon (ta-C) films were prepared on cutters which are used for engraving. Engraving tests were performed on metal plates using non-coated and ta-C-coated cutters, under dry machining conditions, without oil. Generally, the metal plate is engraved using a cemented carbide (WC-Co) cutter, which uses oil for the cutting process, to fabricate a nameplate. The oil causes a high environmental load and complicates the machining process. Therefore, from an industrial viewpoint, there is a need for a dry machining process. The ta-C film is a hydrogen-free diamond-like carbon film with a high mechanical hardness. In this study, droplet-free ta-C films were prepared on WC-Co cutters using a T-shape filtered arc deposition method. The work materials used in the engraving tests were aluminum, copper, and brass. The results of the engraving tests demonstrated suppression of metal adhesion to the cutting edge, prevention of chipping of the cutting edge, and a decrease in cutting resistance during engraving when a ta-C film had been coated onto the cutting edge. In addition, burr and residue on engraved grooves were also suppressed by using a ta-C-coated cutter. The ta-C film coating offered a remarkable improvement in the engraving performance of a WC-Co cutter in the dry machining process.

1. Introduction

In metal machining such as in nameplate fabrication, a cemented carbide (WC-Co) cutter is used with oil for engraving. In the fabrication of the nameplate, the remaining oil on the nameplate is washed away after the engraving process is complete. Then, the nameplate is finished by inking into the engraved groove. This machining process which uses oil is known as “wet machining.” Wet machining requires processes such as the application and removal of oil. It also creates environmental effects such as pollution and destruction of the natural environment. A machining process without oil is known as “dry machining” [1]. However, it is difficult to engrave and cut metal without oil using traditional cutting tools such as a cutter, drill, and end mill due to high cutting resistance between the cutting edge and the work material.

The materials used in nameplate manufacturing are aluminum, copper, brass, and so on. In particular, aluminum is often used as a work material for cutting tools including drills and end mills. During the dry machining of aluminum, adhesion of the aluminum work material to the cutting edge reduces machining accuracy [2]. Adding a film coating to the cutting tool surface can help prevent aluminum adhesion [3,4].

Diamond-like carbon (DLC) is an amorphous carbon containing diamond (sp^3) and graphite (sp^2) microstructures [5,6]. A sp^3-rich DLC, composed only of carbon atoms, is called tetrahedral amorphous carbon (ta-C). The ta-C films possess excellent mechanical properties such as low friction, high hardness, and high flatness [7–10].

The most common fabrication process for ta-C films is the vacuum arc deposition method. The vacuum arc deposition method can fabricate ta-C films with high hardness and high density. In the vacuum arc deposition method, a cathode spot, which is very active and has a high temperature, is formed when an arc discharge is generated between a cathode and anode [11]. The cathode material evaporates from the cathode spot, and the evaporated cathode material forms an arc plasma. Ions, which originate from the cathode material, are produced in high density between the electrodes when the arc discharge is ignited. The

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vacuum arc deposition method can produce a plasma with a high ion density, but droplets, which are almost electrically neutral micro-size particles, are emitted from the cathode spot [11]. Some droplets become electrically charged as they pass through the plasma [12,13]. The emitted droplets become part of the DLC film during the deposition process. The existence of droplets in the DLC film decreases film properties such as flatness and hardness. To reduce the number of droplets in the DLC film, vacuum arc deposition methods have been developed which have a filter to remove the droplets [11,14–18]. In the filtered cathodic arc deposition method, a substrate is set in the out-of-sight position for the cathode. Charged particles in the plasma, which are generated at the electrodes, advance to the substrate via magnetic transport; droplets are not able to reach the substrate as they are unaffected by the magnetic field due to being electrically neutral. Therefore, the filtered cathodic arc deposition method suppresses the deposition and attachment of droplets onto DLC films.

There exist various filter shapes, which are designed to remove droplets in a filtered cathodic arc deposition system. Of these shapes, the T-shape filtered arc deposition (T-FAD) system possesses the highest filtering function [10–12,19–24]. In the T-FAD, the duct from the cathode to the substrate is shaped like the letter "T." Droplets are filtered from the plasma by bending the plasma at a 90° angle. The droplets which go straight are trapped in the duct opposite the cathode [12,19]. Therefore, the T-FAD system can fabricate ta-C films which are high-density and droplet free.

In this paper, dry machining for metal plates, using a cutter coated with a ta-C film prepared using a T-FAD system, is presented. The ta-C coating cutters were evaluated for the shapes of the cutter edges, engraved grooves, chips, and the value of cutting resistance after engraving tests. The engraving tests were performed using aluminum, copper, and brass plates.

2. Experimental procedure

The ta-C films were deposited on WC-Co cutters (Gravograph, 48,821) by the T-FAD method. The film thickness of the ta-C films was about 500 nm. Fig. 1 shows the schematic diagram of the T-FAD system. The duct and chamber of the T-FAD were pumped out using a turbomolecular pump and an oil rotary pump with a mechanical booster pump. The cutters stood vertically on the ground and were rotated on their axis in a chamber during the deposition process.

Before beginning the process of ta-C film deposition on the cutters, preprocessing was performed on the cutter surfaces to improve the adhesion between the ta-C films and the cutters. In preprocessing, an Ar-dominated carbon plasma, formed by introducing Ar gas [24], was used to bombard the cutter within the T-FAD system under the following conditions: a base pressure of less than 8×10^{-4} Pa, a graphite cathode, an Ar flow rate of 60 sccm, a processing pressure of 0.2 Pa, an arc current of 30 A, a pulsed substrate bias of −500 V (at a frequency of 10 kHz, pulse width of 50 μs, and duty ratio of 50%), and a processing duration of 10 min. After preprocessing, the ta-C films were deposited onto the cutter. The deposition conditions were as follows: a base pressure of less than 8×10^{-4} Pa, a graphite cathode, a processing pressure of less than 2×10^{-3} Pa, an arc current of 30 A, a pulsed substrate bias of −100 V (at a frequency of 10 kHz, pulse width of 20 μs, and duty ratio of 20%), and a deposition duration of 90 min.

The ta-C films were also deposited on WC-Co and Si substrates at the same time as on the cutter in order to analyze the film properties. The nanoindentation hardness and Young's modulus were measured using a nanoindenter (Elionix ENT-2100, $Load_{max}$ 1 mN, Berkovich indenter) and a ta-C film deposited on a WC-Co substrate. The film densities of the ta-C films were measured using an X-ray reflectometer (Philips X'Pert PRO MRD, CuKα) and a ta-C film deposited on a Si substrate. Si was used due to the rough surface of the WC-Co substrate.

The Raman spectra of ta-C films on WC-Co substrates and the cutter were measured using laser Raman spectrometry (JASCO NRS-1000, laser wavelength $\lambda = 532$ nm, laser power 5 mW).

The engraving tests, performed to estimate the effectiveness of the ta-C-coated cutters in dry machining, were carried out using an engraving test machine as shown in Fig. 2. The engraving test machine was a desktop CNC milling machine (Prospec PSF-240-CNC) equipped with a dynamometer (KISTLER, 9272) to measure the cutting resistance. The engraving conditions were as follows: a rotational speed of 2000 rpm, a feed rate of 50–200 mm/min, an engraving depth of 0.1 mm, and an engraving distance of 200 mm. The metal plates used as the work material were made of aluminum (JIS A1050), copper (JIS C1100), and brass (JIS C2801). The engraving tests were used to compare the cutters without (non-coated cutter) and with (ta-C-coated cutter) ta-C film coatings.

In the engraving test, feed rates were varied from 50 mm/min to the machine's maximum feed rate of 200 mm/min. After the engraving test, the cutter edges, engraving grooves, and metal chips were observed using a scanning electron microscope (SEM), laser microscope, and optical microscope. In addition, the cutting resistances experienced during the engraving tests were measured using a dynamometer-equipped engraving test machine. The cutting resistances have three components, which are the feed force (horizontal component force acting in the feed direction, Fx), the principal force (vertical component force acting

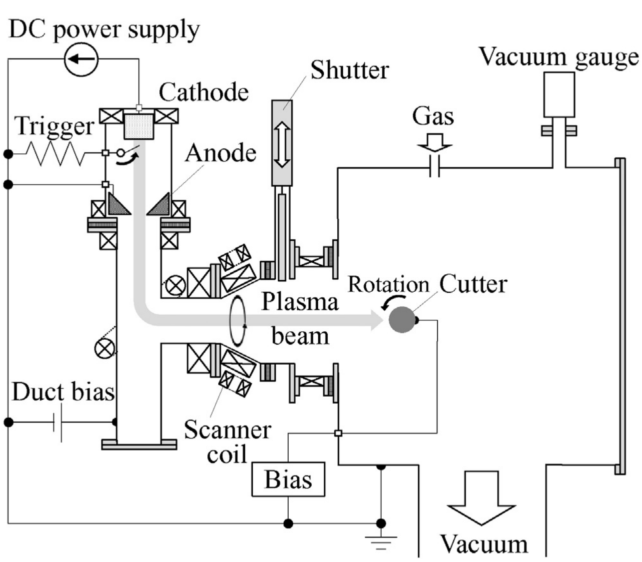

Fig. 1. Schematic diagram of the T-shape filtered arc deposition system.

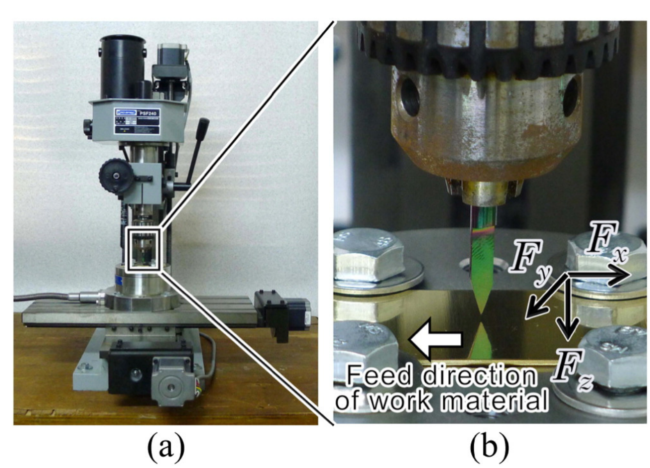

Fig. 2. Photographs of (a) the engraving test machine and (b) the cutter mounting position.