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REGULAR PAPER

Wear-resistive and electrically conductive nitrogen-containing DLC film consisting of ultra-thin multilayers prepared by using filtered arc deposition

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Nitrogen-containing diamond-like carbon (N-DLC) multilayer films approximately 500 nm thick were fabricated on tungsten carbide substrates as surface protective films with high wear-resistive and conductive properties. Each layer thickness of the N-DLC multilayer films was approximately 10 nm, and the films were a periodic bilayer structure consisting of hard and soft N-DLC layers. Owing to the high abrasion resistance of the hard layer and the low aggressiveness and high adhesion of the soft layer, the multilayer films showed good polishing and wear resistances compared with the hard N-DLC monolayer film, and the electrical resistivity was about half. In the case of DLC multilayer films consisting of hard N-free DLC and N-DLC films, the decrease of each layer thickness leads to the reduction of the polishing resistance. From X-ray reflectivity analysis of ultra-thin N-free DLC films, it was indicated that the film density of an ultra-thin N-free DLC film is lower than that of a thick N-free DLC film. In the DLC multilayer film with thin N-free DLC layers, it is possible that the polishing resistance of the whole DLC film reduced because the hardness the N-free DLC layer was decreased due to the low film density of each N-free DLC layer.

1. Introduction

Electrically conductive hard-coating films are required as a protective film on the tip of a contact pin that is used in the electrical inspection process.[1–3] Gold plating, which is the surface protective film of commercial contact pins, has the oxidation prevention of a base metal and high electrical conductivity but poor wear resistance. Also, the protective films of the contact pin are required to have high adhesion resistance for suppressing adhesion of the solder to the tip of the pin during the inspection process.[3]

Diamond-like carbon (DLC) films are amorphous structures that have been widely used as protective-coating films because the films have superior properties such as high hardness, high wear resistance, and excellent adhesion resistance.[4–7] It is thought that a DLC film has sp^2 and sp^3 carbon bonding structures, and its electrical resistivity is high.[8] The typical electrical resistivity of DLC films is known as 10^6–10^8 Ω cm.[9,10] When nitrogen is contained in the DLC film, the electrical resistivity of the nitrogen-containing DLC (N-DLC) film dramatically decreases[3,11–17] however the decrease of the electrical resistivity is dominated by the increase of the electron carrier with increasing of the sp^2 bonding structure rather than that owing to the nitrogen doping in the film. The increase of the sp^2 bonding structure in a DLC film leads to a decrease of mechanical hardness in the film.

Harder N-DLC films in the N-DLC films have been prepared by filtered arc deposition (FAD) methods.[3,18–26] The FAD methods are vacuum arc deposition (VAD) methods equipping a filtering duct for removing fine particles called a droplet generated from a cathode.[3,18] In the VAD method, an arc spot that is active at high temperature is formed on a cathode, and the cathode material evaporates. A thin film is formed by the evaporated cathode material reaching a substrate. As the cathode evaporates, droplets are also generated from the cathode. The droplets mixed in the film significantly degrade the film properties such as flatness and hardness. In the FAD methods, the distance from a cathode to a substrate is long passing through a filtering duct, and the mixing of droplets into a film is prevented.

It has been reported that adhesion to a substrate and wear resistance improved by alternately stacking a hard film and a soft film consisting of a metal film and/or a DLC film.[27–35] The hard film has high abrasion resistance, but cracks and peeling are caused by loads during abrasion. On the other hand, the soft film has inferior wear resistance compared with the hard film, but show good adhesion. A multilayer film stacked alternately a hard film and a soft film is suppressed delamination of the hard film by the high adhesion of the soft film during abrasion, and exhibits high wear resistance as the whole film.[29] In our previous study, the multilayer film consisting of N-free high-density DLC layers and N-DLC layers showed low electrical resistivity and excellent wear resistance.[35] 8-layer DLC film with a N-free high-density DLC film as the top layer was about half the electrical resistivity compared with the monolayer N-free high-density DLC film.

In this paper, the polishing and wear resistances of DLC multilayer films with lower electrical resistivity prepared by using a FAD method are presented. The DLC multilayer films consisting of two kinds of DLC layers had thinner thickness per layer compared with our previous study.[35] Multilayer films with low electrical resistivity were formed with only N-DLC. In addition, the effect of layer thickness on