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Mini Review

A Wear Sensor Based on Nanocrystalline Diamond Multilayer Films: A Mini Review

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Abstract

Major amounts of industrial wear parts, e.g. machining tools, are working under extreme wear load, especially abrasive. This short article reviews the development and fabrication of a well-performing nanodiamond-based multilayer wear sensor system consisting of alternating conductive and non-conductive films. Meanwhile, the deposition and characterization of such highly conductive nanocrystalline diamond films without dopant are also introduced.

Introduction

At present, a large number of automotive and aerospace parts are lightweighting, and made by composite materials with enhanced mechanical properties, e.g. aluminium-based composites or CFRPs (carbon fiber reinforced plastics). Those materials contain larger volume fraction of hard components and thus requiring higher abrasion wear resistance of machining tools. A typical combination of hardness and toughness to meet this requirement is integrating a cobalt-cemented tungsten carbide (WC-Co) tool with diamond coatings via Hot-Filament Chemical Vapour Deposition (HFCVD) [1,2]. However, as soon as the coating is locally detached or totally worn, the regrinding or recoating of worn tools is unfeasible, as the basic substrate's body was already damaged irreversibly. Therefore, a method for only detecting the worn state of the coating itself needs to be developed [3], rather than monitoring the chip formation or tools' cutting force [3]. During the former research, besides outstanding mechanical properties, highly electrically conductive nanocrystalline diamond films with low specific contact resistance were also synthesized after an appropriate HFCVD process and a surface's oxygen reactive-ion etching (O-RIE) subsequently, without further dopant [4]. Based on this, a multilayer nanodiamond film structure consisting of conductive and non-conductive diamond film-layers was developed and fabricated onto WC-Co dummy tools, whereby a linear sensoring response against coating's worn state was also detected electrically [3].

Deposition and Characterization of Undoped Nanocrystalline Diamond Films with High Conductivity and Low Contact Resistance

Instead of chemical doping of the electronic structure of diamond, the electrical conductivity of diamond films introduced in [4] was realised by tailoring their grains' nanostructure formation, which was dominantly controllable only by varying methane (CH_4) composition in the CH_4/H_2 precursor gas mixture. A maximal specific electrical conductivity up to 133.45 S/cm was measured with Van-der-Pauw (VDP) microstructures (Figure 1, left) prepared photolithographically on silicon wafer [4]. In addition, Linear-Transmission-Line-Methods (LTLM, Figure 1- right) was in use, on the one hand, for evaluating conductive diamond films' specific contact resistance (down to 6.98×10^{-6} Ωcm^2) after different metallization and surface treatments; and on the other hand, for identifying the suitable ohmic contact between conductive diamond films and metallization [4].

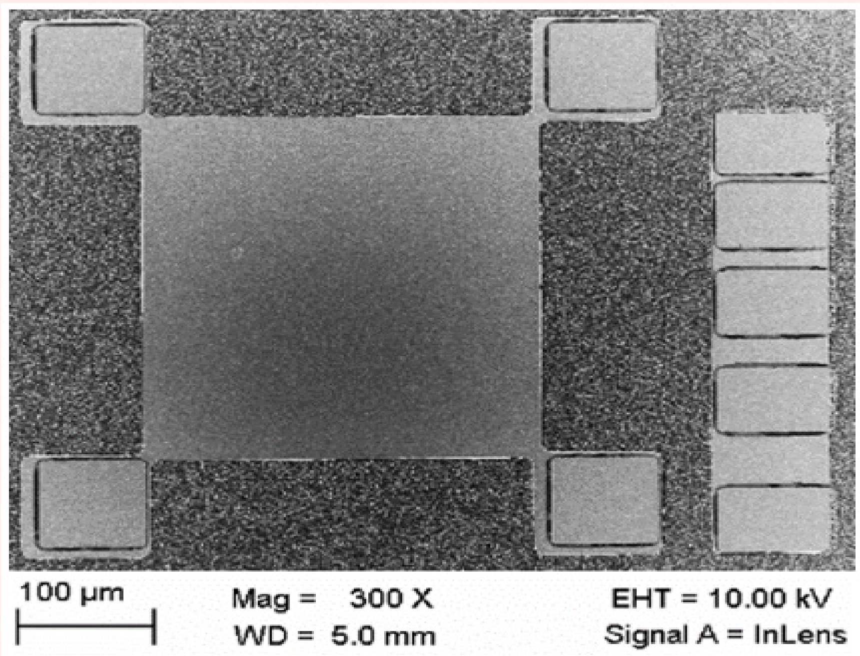
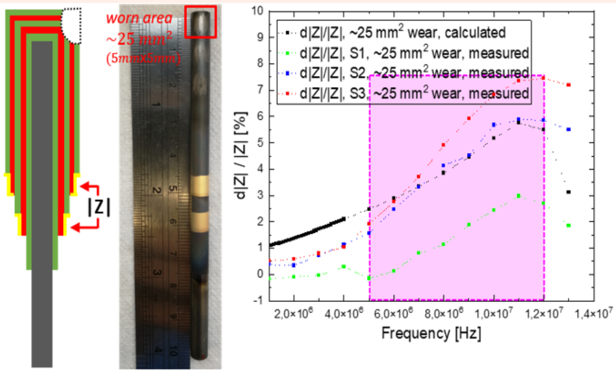


Figure 1: VDP (left) and LTLM (right) micro-structures prepared photolithographically.

X-Ray Diffraction (XRD) and Raman measurements delivered the explanation about those nanodiamond films' specific conductivity as grain boundary dominated, during the decrease of their grain sizes and thus increase of the grain boundary volume with higher content of defective sp^2 carbon sites [4,5]. More insights into the reason and mechanism of reduced surface contact resistance were gained by aid of performing X-ray Photoelectron Spectroscopy (XPS) measurements on them. Apart from the differences of contact metals' work functions, the effective reconstructions of diamond films' surfaces via the O-RIE treatment contributed more particularly sensitive to their surface electron affinity change from the negative range (H-terminated as-grown) to the positive range (O-terminated) [4].

Fabrication and Detection of the Nanodiamond Multilayer Wear Sensor

The basic functional microstructure of the multilayer wear sensor consisted of two conductive nanocrystalline diamond film layers (CNCD with 10 S/cm at 5 nm grain size, red in Figure 2) and one non-conductive nanocrystalline diamond film layer (NCD with 5.4×10^{-6} S/cm at 10-20 nm grain size, green in Figure 2) in between [3]. On top of them was a NCD layer as wear protection. Those two conductive diamond layers functioned as two plates of a capacitor and the intermediate layer worked as the dielectric. Even though the cobalt on the surface of the substrate in use (Ø6 mm WC-Co dummy rod, Co-10w%) was pre-etched [3], its catalysation effect on graphitization and formation of non-diamond phases also would be sped up, if the conductive diamond films were directly deposited onto such substrate, as those films were requiring a relatively high CH_4-ratio [3,4]. Therefore, an additional adhesion layer as deposition start with typically low CH_4-ratio thus bigger diamond grain size was in need, which also enhanced the mechanical interlocking between the film system and the substrate [3]. As to free the ending areas for the two conductive diamond layers for metallization afterwards, the multilayer structure was prepared in a stair-like shape (Figure 2, middle), by covering the grown areas with adjustable copper sleeves during an intermittent deposition process [3]. The aforementioned CNCD's specific contact resistance pressed the practical resistance value of the contacting area down to approx. 7 µm, which was reasonably negligible and simplified the modelling process [3,4].



FFigure 2: Schematic - nanodiamond multilayer sensor's structure and linear sensoring response.

By modelling, the as-grown resistance value of the intermediate "insulating" layer must be considered. Reason for that was the extremely small ratio between its thickness in micrometre scale and its covering area in square millimetre scale, referring to Ohm's law, despite of its low specific conductivity [3]. As a result, the multilayer sensor system was modelled as a "RC-parallel circuit" and the correlation between its loses of the conducting plates' area ΔA resulted from abrasive wear against the capacitance change ΔC (impedance change Δ|Z| in practical measurement) was expected [3]. After scratching a window (roughly 5 mm × 5 mm) on each tested sample (S1-S3) for simulating ΔA, a considerable increase of the relative variation of impedance Δ|Z|/|Z| over frequency was detected (Figure 2, right). Furthermore, a noticeable linear sensoring response detected from three samples was also recognizable and well matching to the calculated curve (plotted in black in Figure 2, right). This linear response area started from the RC-parallel circuit's resonance frequency and ended by the frequency value, from that the impedance's imaginary part was inverting from a capacitive to an inductive resistance effect, as the inductive resistance part was introduced by the applied straight copper cables into the set-up [3].

Conclusion

It has been shown that, a nanodiamond-based multilayer sensor system was controllably and reliably realised, integrated with conductive and non-conductive diamond films via HFCVD technique. A first prototype was applied onto a WC-Co dummy tool, with theoretical model for simulation and practical detection about linear sensitivity. The main benefit of this type sensor was the efficient protection of the wear parts' basic body, as to enable their recoating and reusage. Besides the machining tools mentioned above, more application scenarios could also be considered for those industrial parts, e.g. sliders or forming dies, which are subject to very high wear load.

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