Comparison of Cutting Performance of Router with CrAlSiN and DLC Hard Coatings

Yi Huang, Jin-Shi Zhang, Xiao-Yin Chen, Wei-Yu Ho, and Wei Li

***Abstract*—Milling printed circuit board (PCB) is a quite essential technology of removing areas of copper from a sheet material. The PVD hard coatings are expected to improve milling tools for PCB industry. In this study, the cutting performance of the CrAlSiN and diamond like carbon (DLC) double-layered coating deposited on the micro router was compared by machining the PCB. CrAlSiN coated tool as reference, two other coating systems including CrAlSiN and DLC double layers were deposited by cathodic arc evaporation (CAE) technology. Two different DLC layers were designed with Cr/C and CrN/C multilayer structure. The results shows that both double layered coated tools present the better hardness and cutting performance as compared to the single CrAlSiN coating. The highest improvement of the CrAlSiN + CrN/C double layered coating is nearly triple times higher than that of tool coated with single CrAlSiN layer.**

***Index Terms*—Cathodic arc evaporation, CrAlSiN coating, diamond like carbon, wear.**

I. Introduction

In the past decades, CrAlSiN coatings have attracted an increasing interesting in fields machining applications due to the nanocomposite structure and excellent mechanical properties [1]-[4]. CrAlSiN coating featured with high hardness is widely applied to the cutting tools. The other feature of excellent thermal stability of CrAlSiN is known to result from the formation of Al_2O_3, Cr_2O_3 and SiO_2 phases above the surface retarding the oxidation of the coating [5], [6].

Under increasing requirement of further improve the efficiency of cutting tools, searching for modified coating materials is interesting in many research groups until now. The perspective diamond like carbon (DLC) film is the one kind of the coatings to improve the milling process [7]-[12]. Different kinds of carbon-based coatings are already in use for this purpose. The most efficient hydrogen-free DLC coatings for tool are synthesized by laser ablation, magnetron sputtering and cathodic arc evaporation (CAE) technology. The common feature of these methods is that DLC coatings can be deposited with free content of hydrogen which induces high percent of sp^3 bonds and high hardness. Beside high hardness, DLC may also be attributable to the low steady-state friction coefficient and wear reduction due to the presence of a carbon transfer layer on the wear scars of the contact surface. The CAE is widely used to synthesize the hard coating materials, but also is good for the tetrahedral amorphous carbon (ta-C) and amorphous carbon (a-C) coating materials. Metal/carbon composite films involving metal inert with respect to carbon can be of interest in wear resistant and low friction applications [13]. Currently, combining the excellent properties of the hard nitride coating and DLC coating has attracted some research group to process this novel concept by using cathodic arc evaporation (CAE) [11].

Milling printed circuit board (PCB) is the process of removing areas of copper from a sheet of PCB material to recreate the pads, signal traces and structures according to a digital circuit board patterns. The performance of milling tool for machining PCB is so important that it gains an interest among the research groups. However, hard nitride and DLC coatings do not always produce the expected results for some reasons.

Therefore, the aim of the research presented here is to combine the CrAlSiN and DLC to form as double layered coatings. The interested concept is to improve the milling performance of the coated routers on the PCB.

II. Experimental

Specimens made of tungsten carbide and 304 stainless steel were coated with CrAlSiN and DLC coatings by using CAE technology. After the basic evaluation of the various deposited coatings, the further coating process on the router is tailored in order to meet the necessary thickness for machining the PCB. The router dimension of the blade area used in this study is 1.0 mm in diameter and 10 mm long. The CAE system consists of two sets of standard cathodic arc ion evaporators, auxiliary a circular substrate holder connected with bias power supply. Cr target (purity: 99.9%) and $Cr_{30}Al_{60}Si_{10}$ ((purity: 99.9 at.%) target were used as source materials to synthesize CrAlSiN coating. On the other hand, Cr target (purity: 99.9%) and graphite target (purity: 99.9%) were used as source materials to synthesize DLC coating with different conditions, respectively. Two DLC coatings were designed with Cr/C and CrN/C multilayer structure, respectively. The deposition period of the DLC layer is 10 minutes. The former DLC layer is only introducing Ar gas, while the later DLC layer is introducing the Ar and nitrogen gases during the final process.

The crystallographic structure and texture of the films were investigated by glancing-angle X-ray diffraction (GAXRD), using CuKα radiation at incident angles of 2°. The surface

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morphologies of the coatings were observed by scanning electron microscopy (FE-SEM, model Hitachi, SU8020) and the composition of the coatings is analyzed by using energy dispersive spectrometer (EDS). Raman spectra were recorded with a Raman spectrometer to evaluate the carbon single layer evaporated from the graphite target. The hardness of coatings was measured in a Vicker's indentation equipment with the applied load 25g. Three kinds of the samples were compared by machining the PCB in dry condition. One is CrAlSiN-coated tool which indexed as sample no. S0. The other two are one coated with CrAlSiN + CrC coating indexed as sample no. S1 and the other one coated with CrAlSiN + CrN/C indexed as sample no. S2 by CAE technology. After the cutting test, the PCB boards and tools were to be compared via the cutting distance observed by optical microscope.

III. Results and Discussion

DLC is defined as an amorphous carbon with a significant fraction of sp^3 bonds, and the films produced here are known as hydrogen free amorphous carbon (a-C). Two DLC coatings were designed with Cr/C and CrN/C multilayer structure, respectively. The deposition period of the DLC layer is 10 minutes. After the observation of the cross section area of the fractured DLC coatings, the result shows the similar design of multilayer structure which composes of metal and carbon periodic layers, as shown in Fig. 1 of Cr/C coating.

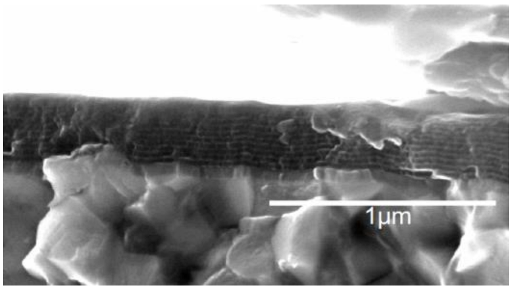

Fig. 1. SEM observation of cross section area of Cr/C multilayer coating.

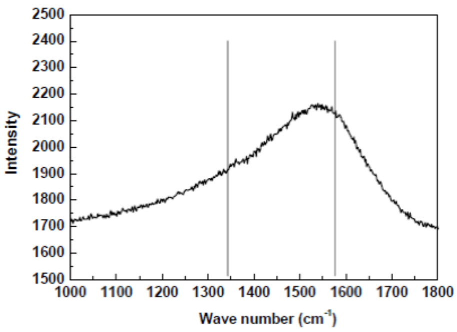

Fig. 2. Raman spectra of the single carbon layer.

Fig. 2 shows the Raman profile investigated by Raman spectroscopy of the single DLC coatings. In the range of 1300–1800 cm^{-1}, there is only one broad band. Usually, the most important bands observed are the D and G peaks, which centered at 1350 and 1580 cm^{-1}, respectively. It is known that the D and G peaks are due to the resonant process of sp^2 sites. The G peak is due to bond stretching in all the pairs of sp^2 atoms located in the crystal lattice (in both the rings and chains), whereas D peak is due to the breathing modes of the sp^2 atoms in the rings [12]. The broader G peak denotes the amorphous structure of the DLC. The ratio of intensities of the G and D bands (I_G and I_D) increases with decreasing sp^2 content. The high I_G/I_D peak ratio appears to be the result of decrease of the crystallite size. On the other hand, it can be inferred from this an increase of the sp^3 content.

The microstructure of the individual CrAlSiN, Cr/C and CrN/C layers is investigated by X-ray diffraction (XRD) analysis, as shown in Fig. 3. Except the pattern of substrate, it can be seen that the CrAlSiN layer is comprised of (111), and (200) crystalline planes. The result means FCC structure of the CrAlN embedded in the SiNx matrix [1-4]. As for the other two DLC layers, the XRD results show no obvious diffraction peak except the substrate. The result reveals the amorphous structure of the DLC layers.

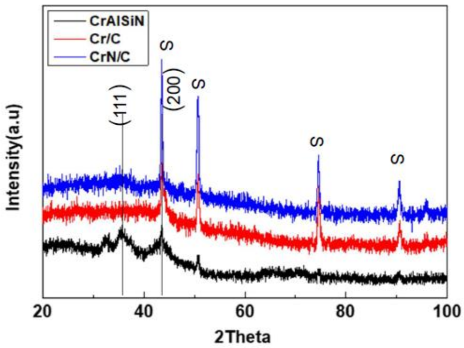

Fig. 3. XRD analysis of various single layer on 304 stainless steel substrate.

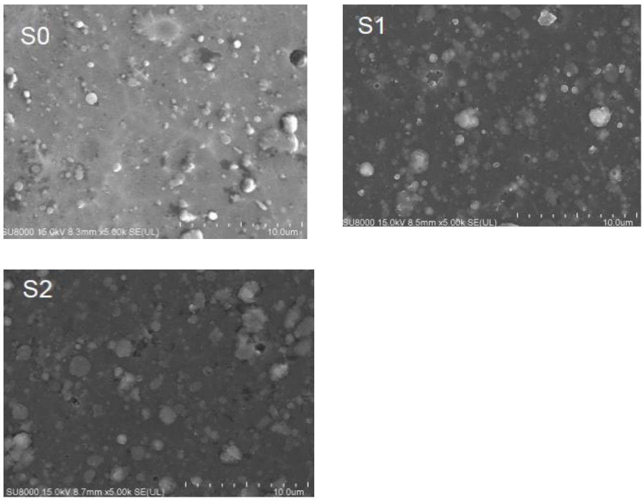

Fig. 4. Surface morphology of the coatings. S0: CrAlSiN, S1: CrAlSiN +Cr/C, S2: CrAlSiN + CrN/C.

The SEM micrographs of the coating surface shows a dense morphology of the three coating systems, showing the microdroplets spread on the surface, as shown in Fig. 4. Due to the disadvantage of the CAE technology, the droplets formed during deposition from the CrAlSi and graphite cathode are randomly distributed on the coating surface in small sizes, varying from a fraction of a micrometer to 2 µm. The composition of CrAlSiN layer was verified by EDS scanning analysis showing the composition of the coating (Table I). The composition ratio of the S0-CrAlSiN is 24.34 of Cr, 27.27 of Al, 4.94 of Si and 28.24 of N (at.%), respectively. The metallic composition ratio of the CrAlSiN is in agreement with the CrAlSi target but not in the same ratio. The rich Cr and Al elements of the CrAlSiN reveal the lower hardness of Hv3537 as compared to the coating with rich nitrogen content [2]. The Cr/C layer contains the higher carbon content of up to 77% than CrN/C layer of 56%. For the CrN/C layer, the nitrogen element may dominate preferable atomic site to the carbon atom. The hardness of the S2 which the coating composed of CrAlSiN and CrN/C double layers is about HV4352, obvious higher than that of CrAlSiN coating and S1. The presence of sp^3 bonds in amorphous carbon film and CrN nitride induces the advantage of the DLC (CrN/C) layer with higher hardness results in increase of the S2 coating hardness [11].

TABLE I: THE COMPOSITION, ROUGHNESS AND HARDNESS OF THE VARIOUS COATINGS

Item	S0	S1	S2
Cr(at.%)	24.34	15.67	12.01
Al(at.%)	27.27	5.96	4.62
Si(at.%)	4.94	1.04	0.81
N(at.%)	28.24	0	22.86
C(at.%)	11.42	77.34	56.51
O(at.%)	3.79	0	3.10
Hv(25g)	3537	3484	4325

Fig. 5 shows the coefficient of friction (COF) of the various coatings deposited on WC-6%Co substrates against WC ball. The COF of S0 was down to 0.3. In the case of S1 with Cr/C on top, the improvement of the COF of 0.15 was seen. For the S2 sample with CrN/C layer on top, the COF of 0.25 was slightly increased as compared to S1. The main benefit of S1 layer is related to the high carbon content up to 77 at.% and estimated high percent sp^2 cluster. As for S2, the lower content of carbon may lead to the higher COF. However, both the samples with DLC layer on top shows the better COF value. Therefore, in addition to hard protective coatings, appropriate lubrication of carbon content during sliding contacts is needed to reduce the friction coefficient and thereby the wear rate of materials.

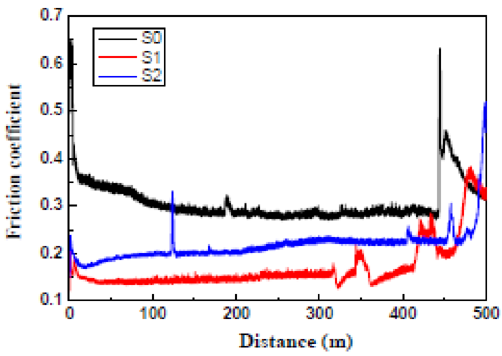

Fig. 5. Shows the coefficient of friction (COF) of the various coatings deposited on WC-6%Co substrates against 6 mm in dia. WC ball.

Fig. 6 also shows the optical observation of the wear track of the coatings after wear test. The wear mechanism of the coatings against WC ball is in quite good agreement with the abrasive wear mechanism. The wear resistance of the coatings was compared by estimating the width of the wear track. It can be inferred that the increasing COF increased the effect of wear damage. In addition to the COF during wear test, the wear resistance of the different samples can be compared by the worn width of track which shows the narrow width happened on the S1 and S2 coating but wider worn width on the S0.

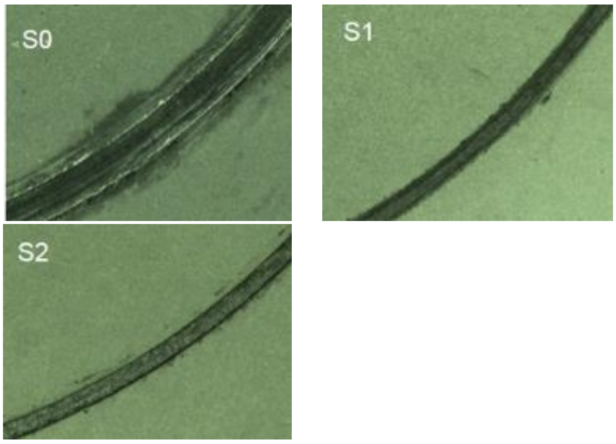

Fig. 6. The optical observation of the worn tacks of the various coatings. after pin-on-disc tribological test.

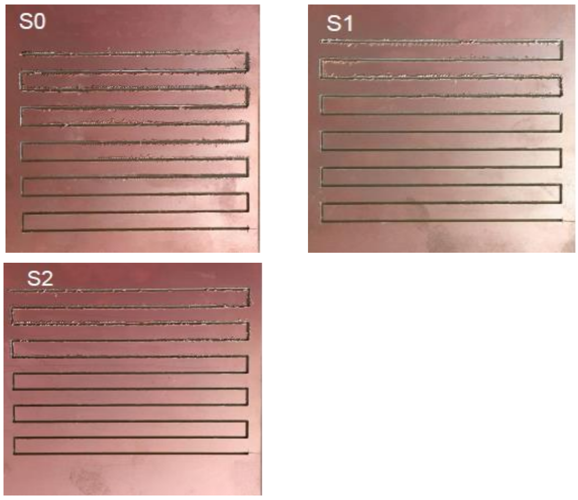

Fig. 7. Optical microscope observation of the PCB cut tracks.

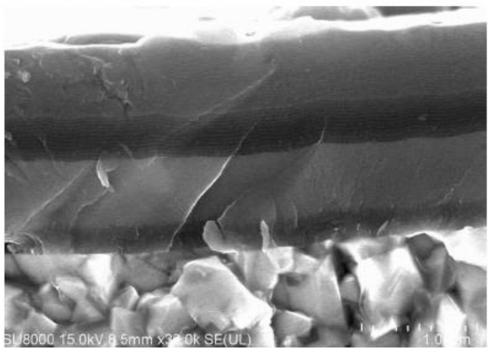

Fig. 8. The cross-section observation of the S2 sample showing the combination of CrAlSiN and CrN/C layers.

The cutting tests for the tool with various coatings against PCB are shown in Fig. 7. The cutting failure is defined in the mode of copper debris built up along PCB trench under same condition. Three kinds of tools were tested including CrAlSiN-coated tool (S0), tool with CrAlSiN + Cr/C coating (S1) and CrAlSiN +CrN/C coatings (S2), respectively. In case of CrAlSiN-coated tool, the shorter cutting distance was seen. In contrast, S1 samples exhibit the obvious longer cutting distance, increasing 2.45 times of distance. The S2 samples exhibited the longest cutting distance up to 2.85 times as compared to the S0 samples. The cross-section observation of the S2 sample shows the combination of CrAlSiN and CrN/C layers has the dense structure appearance, as shown in Fig.8. At the same time, it is confirmed that the adhesion of the whole coating on the WC-Co substrate is excellent. Therefore, the main reason of increasing cutting distance is based on the higher hardness of the coating. Although, the hardness of S0 and S1 are of the similar level, the compensation of the COF of S1 coating led to a significant improvement in the cutting performance. S2 with the best hardness and second best of the COF led to the best cutting performance on the cutting distance of router against PCB. To further investigate cutting performance, optical microscope was used to observe the worn tool after machining of the PCB (Fig. 9). Among the three samples, the worn tool of S0 showed the most worn behavior in shorter distance, which could be related to the lower hardness and higher COF of the coating. This suggests that hardness and friction coefficient of the coating had influenced on the worn out of the tool during the cutting contact. The tool with CrAlSiN + CrN/C coating presented a longest life which could be attributed to higher hardness and lower friction coefficient contacting PCB during test.

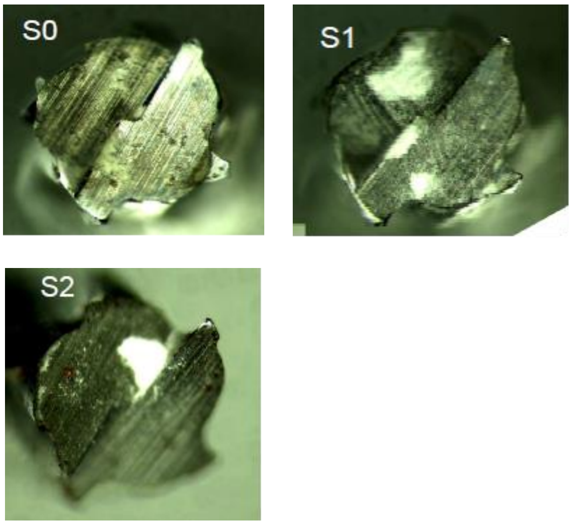

Fig. 9. The observation of the tools after the cutting test.

IV. CONCLUSIONS

CrAlSiN and DLC coatings were obtained by using cathodic arc evaporation technique with Cr, CrAlSi and graphite targets. As compared to the CrAlSiN coating, the hardness of CrAlSiN + CrN/C double layered coating with the highest hardness and the second best COF value. After the cutting PCB test in dry condition, the microtool with CrAlSiN + CrN/C double layered coating exhibited the best cutting performance related to the cutting distance.

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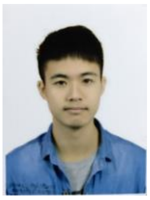

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