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STRUCTURE AND MECHANICAL PROPERTIES OF DIAMOND-LIKE CARBON (DLC) COATINGS DOPED WITH SILICON

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This paper reports the study of silicon-doped diamond-like carbon coatings a-C:H:Si prepared by Plasma-Assisted Chemical Vapour Deposition (PACVD) on 100Cr6 steel. Surface morphology and elemental composition were determined with the use of Scanning Electron Microscopy (SEM) / Energy Dispersive Spectroscopy (EDS). Surface topography measurements were performed using Atomic Force Microscopy (AFM). The scratch test assessment of the influence of a-C:H:Si coatings on mechanical properties was based on the measurements of nanohardness and adhesion to the substrate. The results show that silicon-doped diamond-like carbon coatings a-C:H:Si are characterized by a uniform surface structure, high hardness and good adhesion to the substrate.

Key words: DLC coatings, silicon, friction, wear, hardness

INTRODUCTION

Robust performance of parts of machines and plants relies primarily on the engineering materials used and mechanical loads they carry. Currently, special requirements are placed on functional surface layers, which are responsible for proper operation under variable loads. They are most often obtained in the processes of Physical or Chemical vapour deposition (PVD, CVD, respectively), usually enhanced by plasma. In order to improve the functional properties of friction nodes operating under high loads, thin layers of amorphous hydrogenated carbon (a-C:H), called diamond-like carbon DLC, are increasingly used, attracting attention of both researchers and industry. The attractive properties of DLC coatings include low coefficient of friction, high wear resistance, high values of hardness, corrosion resistance and thermal stability [1, 2]. Excellent mechanical, chemical and electrical characteristics of DLC coatings make them suitable for application on highly-loaded components of friction pairs. Various chemical elements can be incorporated into the coatings with no change to their amorphous character. Metals and nonmetals such as N, Si, F, O, W, Co, V, Mo, Ti, and their combinations can be used as dopants. The DLC coatings have found applications in electronics as protective films for magnetic hard disc drives, compact disc (CD) or digital video disc (DVD) matrices, and so on. In the automotive industry, they are used for engine components, cam-follower interfaces, piston pins, and clutch elements. In medicine, DLC coatings are applied on components with surfaces in contact with blood, such as valves, stents, blood pumps, implants in knee, hip and arm joints. DLC coatings protect machine parts in the textile industry and dies in injection moulding [1, 3-5]. From a tribological perspective, a silicon-doped DLC (a-C:H:Si) is an excellent material, characterized by a very low coefficient of friction in humid atmospheres and at high temperatures [2].

In CVD methods, an a-C:H:Si coating was synthesized using organic precursors such as hexamethyldisiloxane (forming SiO-DLC), tetramethylosilane and toluene [2] and prepared via doping silicon by sputtering [6-11].

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MATERIALS

The test samples were made of 100Cr6 steel and had DLC a-C:H and a-C:H:Si coatings produced by PACVD at 300 °C. The chemical composition of steel 100Cr6 is shown in Table 1.

Table 1 **Chemical composition of 100Cr6 steel / wt. %**

C	Mn	Si	P	S	Cr
0,95 -1,10	0,20- 0,50	max -0,35	max -0,025	1,30 -1,60	1,30-1,60

RESULTS AND DISCUSSION

Topography of the a-C:H and a-C:H:Si surfaces, investigated using an atomic force microscope, is shown in Figures 1 and 2. Isometric images of the coating surfaces are in Figures 3 and 4.

Surface topography of a-C:H and a-C:H:Si coatings proved their very good quality. The slight elevations on the a-C:H:Si surface were most likely due to silicon inclusions.

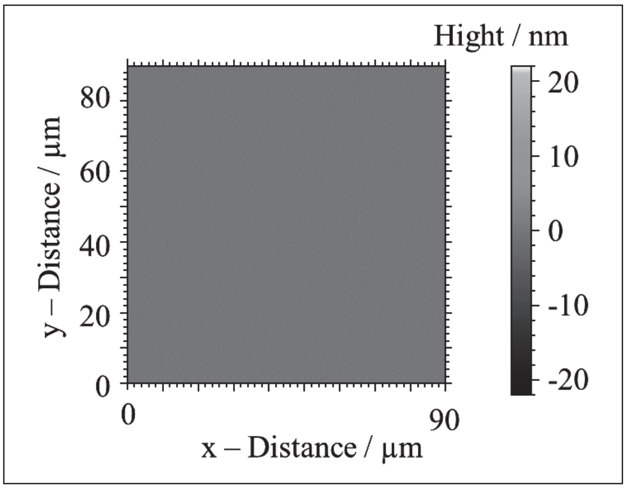


Figure 1 Topography of a-C:H coating surface

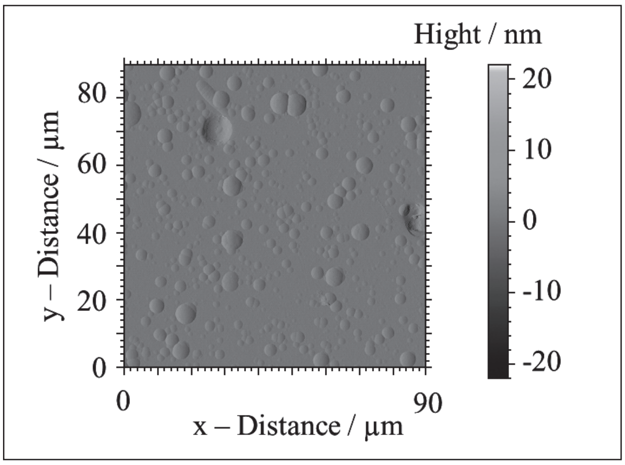


Figure 2 Topography of a-C:H:Si coating surface

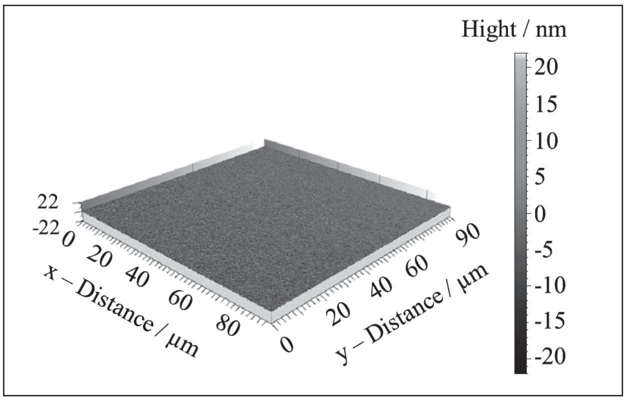


Figure 3 Isometric image of a-C:H coating surface

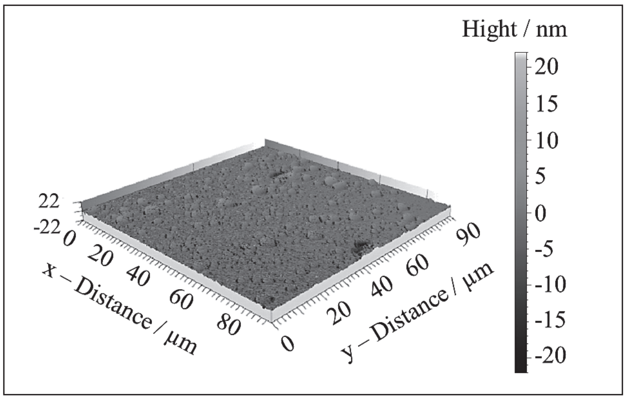


Figure 4 Isometric image of a-C:H:Si coating surface

The cross sections of samples coated with a-C:H and a-C:H:Si were observed using scanning electron microscopy (SEM). Figures 5 and 6 show the SEM images

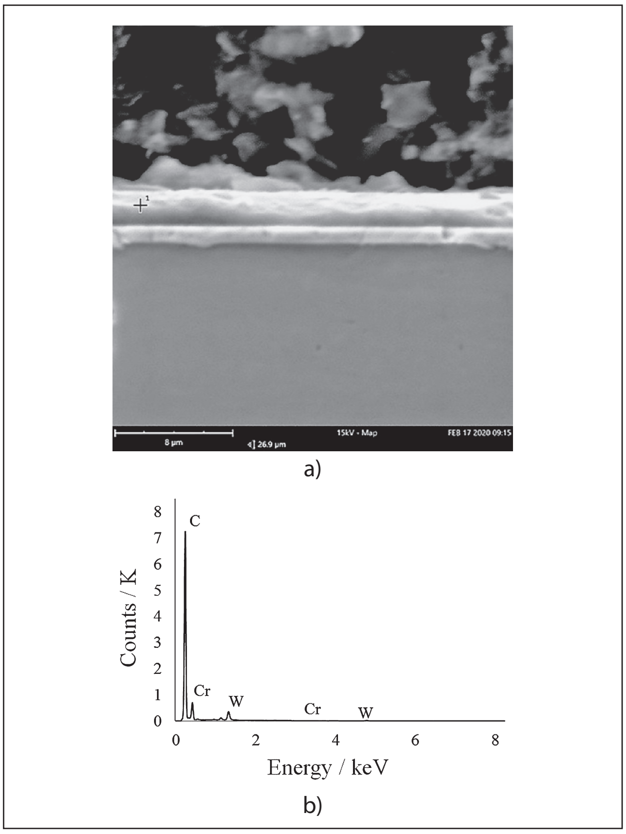


Figure 5 SEM analysis of a-C:H a) cross section; b) EDS spectrum

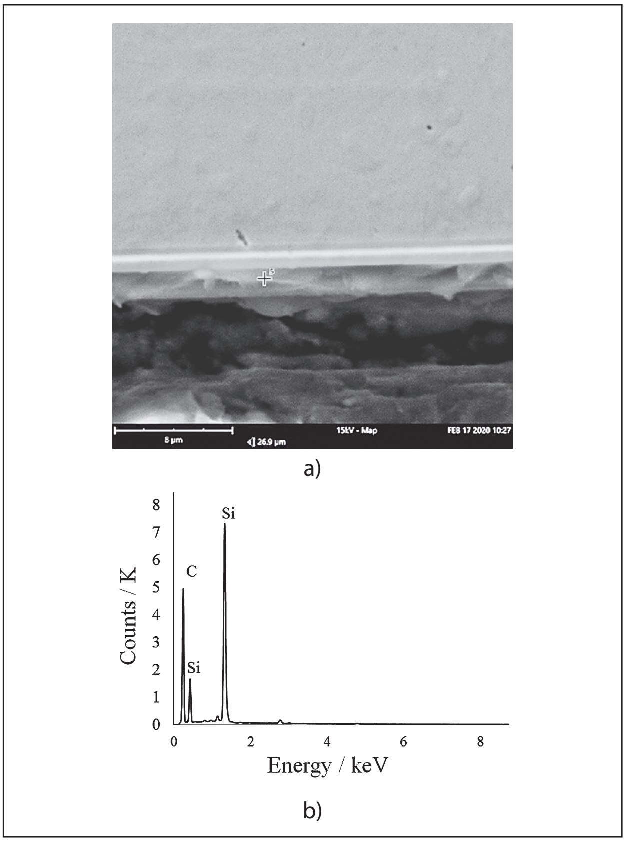


Figure 6 SEM analysis of a-C:H:Si a) cross section; b) EDS spectrum

and corresponding EDS of type a-C:H and type a-C:H:Si coatings.

Point analyses of the chemical composition of the coatings, Figures 5, 6, confirmed the compositions were in good agreement with that established at the manufacturing process.

Nanohardness tests were performed with a Berkovich indenter in a nanoindentation tester NHT3 at a maximum load of 10 mN. The nanohardness of a-C:H and a-C:H:Si was determined from the loading/unloading curve in Figure 7. The Oliver and Pharr method [9] was used to analyse the mechanical parameters. Average values of hardness coefficient for both coating types were determined and shown in Table 2. Figure 8 a and b show the surfaces of a-C:H and a-C:H:Si coatings after the hardness tests.

No images of contact impressions formed by the indenter were observed in the microscope after hardness measurement – Figure 8 a and b. Table 2 compiles the average results of the instrumented hardness tests and Vickers hardness tests for the substrate and both coating types. The a-C:H coating had a considerably higher hardness (nearly 40 %).

The coating-substrate adhesion was examined with a scratch test. Figures 9 - 10 show the coefficient of friction, loading force and acoustic emission as a function of the scratch length recorded during the scratch test for a-C:H and a-C:H:Si coatings. Signs of me-

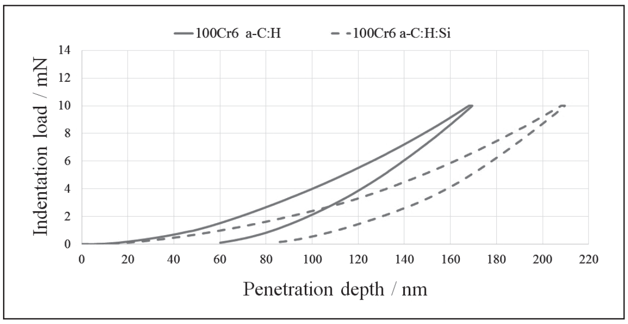
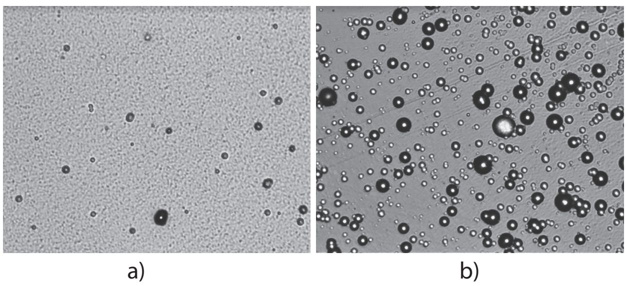


Figure 7 Comparison of a-C:H and a-C:H:Si loading-unloading curves

Table 2 **Average values of hardness coefficients**

Coating	Instrumented hardness indentation HIT / GPa	Instrumented Vickers hardness indentation / HV
a-C:H	23,19	2 147
a-C:H:Si	14,28	1 322



a) b)

Figure 8 Coating surface: a) a-C:H, b) a-C:H:Si after hardness measurement

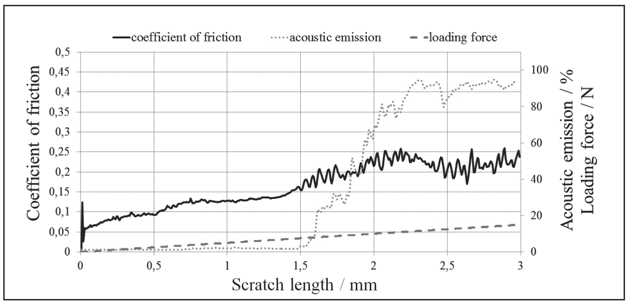


Figure 9 Friction coefficient, loading force and acoustic emission as a function of the scratch length in a-C:H

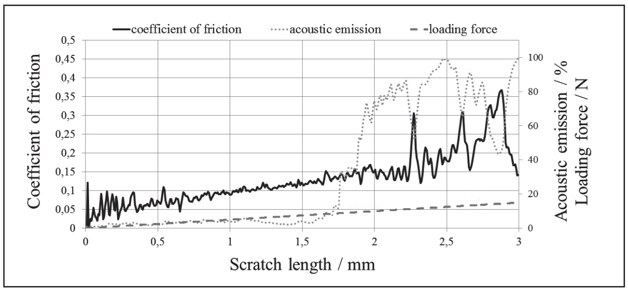


Figure 10 Friction coefficient, loading force and acoustic emission as a function of the scratch length in a-C:H-Si

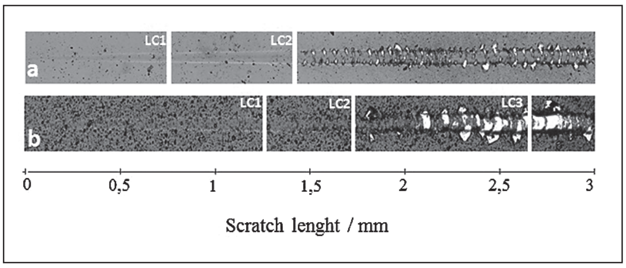


Figure 11 Mechanical damage in coatings: a) a-C:H, b) a-C:H:Si during the scratch test

Figure 12 Indenter penetration depth versus scratch length in a-C:H

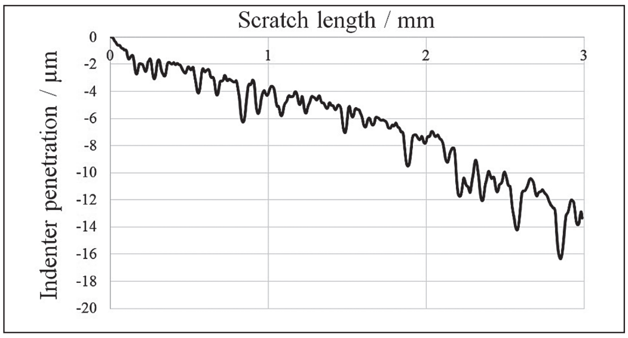


Figure 13 Indenter penetration depth versus scratch length in a-C:H

chanical damage to the coatings during the test are shown in Figure 11. The indenter penetration depth versus scratch length in a-C:H and a-C:H:Si coatings is shown in Figures 12-13.

As shown in Figure 9, the first crack in a-C:H occurred at 3 024 mN (Lc1), and the first chipping (Lc2) appeared at the load of 4 521 mN. No signal corresponding to the delamination of the coating (Lc3) was recorded. As shown in Figure 10, the first crack in a-C:H:Si occurred at the load of about 7 000 mN (Lc1), and the first chipping appeared at 7 515 mN (Lc2). Full chipping occurred at about 9 012 mN (Lc3), when the a-C:H:Si coating showed complete delamination. The penetration depth for a-C:H:Si, about 5 μm, was far greater than that for the a-C:H coating.

The average friction coefficient recorded during the test was 0,16 for a-C:H and 0,09 for a-C:H:Si. The a-C:H:Si coating during the scratch test showed the friction coefficient of half that for the a-C:H coating.

CONCLUSIONS

Analysis of surface topography showed a very good quality of both types of DLC coatings. The elevations visible on the a-C:H:Si surface were from silicon inclusions, as confirmed by the results of the chemical composition analysis.

Nanohardness tests revealed that the hardness of the pure a-C:H was higher than that of the silicon-doped coating.

The results of adhesion tests confirmed that the friction coefficient obtained for a-C:H:Si was nearly half that for a-C:H. Compared with a-C:H, the first chipping in the a-C:H:Si coating occurred at a noticeably higher force.

Diamond-like carbon coatings strongly improve the performance of 100Cr6 bearing steel by increasing its hardness and surface layer wear resistance.

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Note: Translated by Nina Kacperczyk, Kielce, Poland