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The influence of the surface texture of hydrogen-free tetrahedral amorphous carbon films on their wear performance

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ABSTRACT

Hydrogen-free and predominantly tetrahedrally bonded amorphous carbon thin films (ta-C) are excellent coatings to protect surfaces from wear due to their low coefficient of friction and high hardness. Since these coatings may be several times harder than common engineering materials counterpart wear can be significant. Therefore the surface texture of the ta-C coating is critical to wear applications. While the surface roughness is an important factor, the paper shows that other surface texture parameters have to be considered as well to predict the wear performance of the coating. Wear data are compared of as deposited, polished and brushed ta-C coatings. The results show that typically referenced average values for the surface roughness such as R_a and R_z may prove insufficient to reliably predict the wear behavior of the coating. Additional parameters describing the surface texture such as the “Skewness” (R_{sk}) and “Kurtosis” (R_{ku}) can provide relevant information. For example, a brushed ta-C surface with an average roughness of $R_a = 31$ nm showed a tenfold improved wear performance over a polished ta-C surface with an average roughness of $R_a = 10$ nm. This phenomenon is explained by analyzing the R_{sk} and R_{ku} data, which prove to more closely capture the post-treatment specific changes to the surface texture of the coatings.

1. Background

The surface texture of thin films and ta-C in particular varies according to the deposition technology. Cathodic arc evaporation for example may produce an as-deposited average surface roughness (R_a) exceeding 100 nm due to the incorporation of growth defects into the amorphous film structure. Subsequent wear testing shows frequently a run-in effect in the form of an initially increased coefficient of friction, which reduces to a low friction steady state once the surface features are polished away during the test.

The presented study here is based on a series of experiments to develop an industrial coating solution for ta-C coated medical implant components. Previous results showed a direct correlation of surface roughness and wear [1]. Surfaces as-deposited yielded three orders of magnitude higher wear rates than coatings that were polished prior to the wear test. Therefore the need for post-processing of the films becomes essential. To establish a baseline of the biomechanical performance of these ta-C coatings, a 1 million cycle hip joint simulator test was performed. Coated and uncoated chromium molybdenum steel (Co28Cr6Mo) femoral heads were tested in bovine serum running against cup inserts made from ultrahigh molecular weight polyethylene (UHMWPE). Although the coated heads were polished prior to the test they caused about 50% more wear of the polyethylene cups in comparison to the uncoated alloy, which was attributed to the surface roughness of the coated heads. The goals of the current work were to further reduce the roughness of the ta-C coatings and to establish evidence of improved wear performance. For this purpose the polishing process was refined and brushing was evaluated as an alternative post-processing method.

2. Materials and methods

The tested ta-C films were produced using a laser pulse controlled cathodic arc physical vapor deposition (PVD) process technology [2], which is integrated in a commercial PVD unit. A laser pulse evaporates the target material (pure graphite) to trigger a high current vacuum arc discharge. The resulting arc plasma rapidly expands toward the substrate at kinetic energies averaging several tens of electron volts. The process promotes the formation and stabilization of predominantly diamond-like sp^3 bonds in the deposited carbon films.

The substrate material was medical grade Co28Cr6Mo. Flat disks with a diameter of 1 in. were produced for the tests. In order to eliminate substrate effects the surface was polished to a mirror-like finish. The samples were washed and plasma cleaned to ensure proper adhesion of the films. A conventional direct current cathodic arc process was used to deposit a chromium-carbon interlayer to promote stress relieve and adhesion between substrate and ta-C coating. The thickness of the deposited ta-C films was 6 µm. After the deposition

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some of the samples were polished with commercial diamond polishing equipment. Others were brushed with a metal wire brush. The polishing is a multi-step process using diamond powder in ethylene glycol slurry. The grain size of the diamond powder is gradually reduced down to a 1 µm final grit. Followed by these lapping steps the surface is finished by polishing with colloidal silica water slurry. The brushing on the other hand is a 1 step process without additional abrasives. As-deposited as well as uncoated samples were used for comparison.

Optical white light interferometry (Veeco WYKO NT8000) and mechanical stylus profiling (Veeco Dektak 6 M) were used to analyze the surface topography. In addition to traditionally used values such as R_a and R_z an extended range of surface texture parameters was investigated to reveal differences in the surface characteristics caused by each post-treatment. Although wear often correlates with the average surface roughness, especially in case of hard coatings [3,4], topographic surface features play an important role in many applications. Menezes et al. [5–8] compared up to 25 influencing roughness parameters with the resulting friction. For this study the additional roughness parameters R_{sk} and R_{ku} were evaluated. According to ANSI/ASME and ISO standards [9,10] R_{sk} defines the “Skewness” of the surface profile and refers to the distribution in relation to the mean line. R_{ku} stands for “Kurtosis” and describes the “sharpness” of the surface. Both values are used to describe the actual bearing surface.

Wear tests in correlation with the surface finishes were performed with a ball-on-disk tribometer. The tests were performed at room temperature (23–25 °C) under dry conditions (23–29% humidity). The total sliding distance was set to 160 m with a stroke length of 4 mm and reciprocating disk motion. A load of 5 N was applied to balls made from Al_2O_3 with a diameter of 3.175 mm. After the tests the disks and balls were analyzed by stylus profilometry and optical microscopy to calculate the volumetric material loss and individual wear rates.

3. Results and discussion

For a baseline comparison the surfaces as used in the hip joint simulator test were analyzed with respect to their roughness (Table 1). The roughness data of uncoated femoral heads were R_a = 10 nm and R_z = 100 nm. The ta-C coated heads with a post-polished surface finish yielded R_a values >20 nm and R_z values >600 nm. The higher roughness of the coated femoral heads explains the increased wear of the polyethylene cup inserts measured during the hip joint simulator test. With advanced polishing using diamond polishing equipment it was possible to produce ta-C films with a surface roughness in the range of the uncoated reference substrate.

The brushing process on the other hand creates a very smooth appearing surface as shown in Fig. 1d. However, the measured roughness does not correlate with the appearance. Although the height of the surface profile expressed by R_z was reduced to 336 nm, the average roughness R_a measured with 31 nm indicates a higher surface roughness in comparison to the polished head used in the hip joint simulator test (Fig. 1a) and to the polished surface (Fig. 1c).

Table 1
Roughness values for different surface finishes.

Surface	R_a [nm]	R_z [nm]
Co28Cr6Mo uncoated*	10	100
ta-C as-coated	203	2559
ta-C polished[a]	24	614
ta-C polished (advanced)	16	156
ta-C brushed	31	336

[a] Tested in Hip Joint Simulator (HJS).

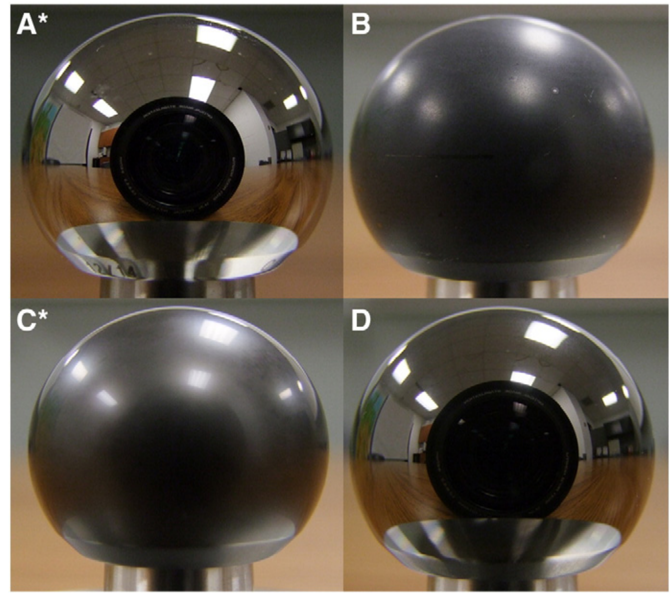

Fig. 1. Co28Cr6Mo Femoral head, A) uncoated B) as-coated C) polished D) brushed. * Heads tested in hip joint simulator.

The ball-on-disk tribometer study compared uncoated, as-coated, polished (advanced) and brushed surface finishes. The results of the tests are compiled in Fig. 2. As expected the uncoated Co28Cr6Mo showed the highest wear rates (2.08×10^{-4} mm^3/Nm) of all material combinations as well as for each counterpart. The ta-C film reduces the wear rate more than ten times (1.10×10^{-5} mm^3/Nm). However, the rough coating causes significant wear of the Al_2O_3 balls. The wear rate of the balls is more than three times higher than the wear rate of the coated disk (8.50×10^{-6} mm^3/Nm vs. 2.53×10^{-6} mm^3/Nm). By polishing the coating the wear rate is reduced by almost another factor of ten to 2.45×10^{-6} mm^3/Nm and the abrasion of the ball decreased approximately one hundred times. The brushed surface showed the lowest wear rate of all tested combinations. The total wear rate (2.75×10^{-7} mm^3/Nm) is ten times lower in comparison to the smoother polished ta-C and one thousand times lower than uncoated CoCrMo.

The results clearly show that the “rougher” (based on R_a and R_z) brushed surface shows less wear than the smoother sample. An explanation for this unexpected result can be found by the surface

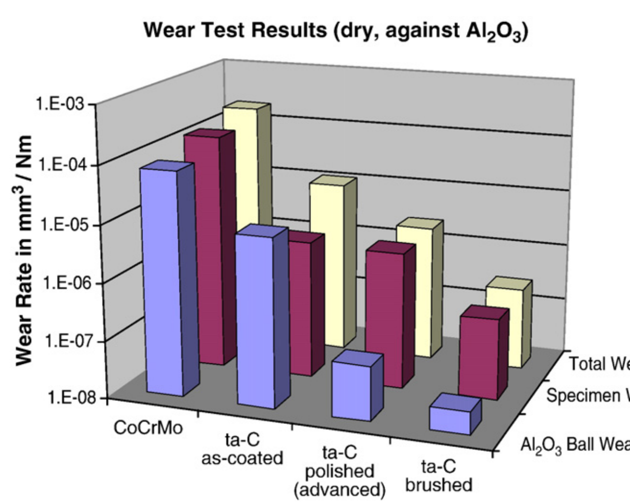

Fig. 2. Pin-on-disk tribometer study.