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Synthesis of diamond-like carbon coating by ion beam deposition: investigation of bioactivity behavior

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Abstract

In this research, a diamond-like carbon coating was created by an ion beam deposition process on the surface of 316L medical steel to evaluate its bioactivity behavior in a simulated body fluid (SBF) solution. Raman analysis was used to investigate and form a diamond-like carbon coating. The morphology and surface roughness of the coating were investigated using field emission scanning electron microscopy (FE-SEM) and atomic force microscopy (AFM). The bioactivity behavior of the coating was evaluated by immersion in SBF solution. The results of Raman analysis showed the formation of a diamond-like carbon coating. FESEM and AFM observations of the diamond-like carbon coating surface showed the formation of a continuous coating without cracks and with a surface roughness of 4 nm on the surface of 316L stainless steel. The results of immersion in SBF solution by FESEM and EDS indicated the formation of calcium phosphate compounds and the creation of apatite layers on the surface of the diamond-like carbon coating.

Keywords: diamond-like carbon, bioactivity, apatite, ion beam deposition.

1. Introduction

Like the tools and components of engines and industrial parts, controlling the surface properties of medical implants by using appropriate coatings to increase their efficiency is of particular importance [1]. One purpose of using coatings is to prevent joint surface wear [2]. Having desirable mechanical properties in metal alloys has led to their use in the repair or reconstruction of bone tissue in the form of implants [1,2]. The main problems of these implants include corrosion and mechanical wear. The physiological environment of the body (PH=7.4 and temperature 35 degrees Celsius) contains oxygen and organic components as well as various salts [3]. Performing surface treatment and creating a coating can be an alternative to prevent corrosion and increase resistance against mechanical wear [1-3]. Diamond-like carbon with a combination of ideal chemical and mechanical properties, including low friction coefficient, high hardness, chemical neutrality, corrosion resistance, and high biocompatibility, has provided opportunities for application in medical implants. The pseudo-diamond carbon coating consists of a lattice of carbon atoms with cross-links of sp^2 (graphite) and sp^3 (diamond) hybridization [4,5]. Many types of research have proven that DLC films can be used to improve the tribological properties of orthopedic implants [6], but very few reports have been presented by researchers on the osteogenesis of Diamond-like carbon (DLC) films in vivo or in vitro. Therefore, in this research, the bioactivity performance of diamond-like carbon coating has been investigated by the ion beam deposition process. Figure 1 shows the application of diamond-like carbon coating on the surface of hip and knee joint implants.

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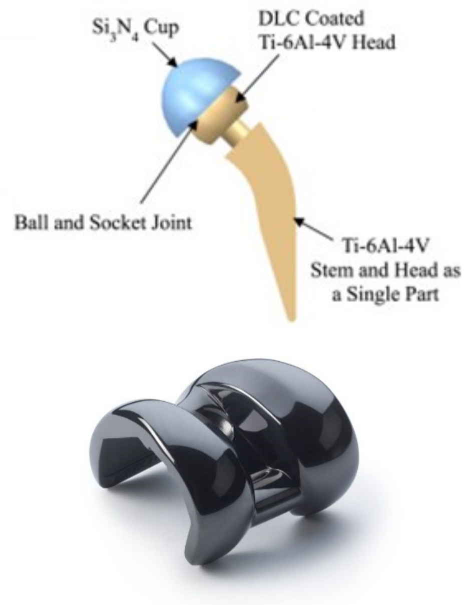


Fig1- application of diamond-like carbon coating on the surface of hip and knee joint implants(7).

2. Materials and experimental

In this research, medical stainless steel 316L was used as a substrate to apply diamond-like carbon coating. The samples were polished with 80 to 3000-grit sandpaper and then washed in an acetone solution in an ultrasonic bath for 20 minutes at a temperature of 40°C and a frequency of 40 kHz. An ion beam deposition process with a radio frequency source was used to deposit diamond-like carbon thin layers. Acetylene gas (C_2H_2) with a purity of 99.99% was used as the hydrocarbon precursor of the pseudo-diamond carbon coating for layering. Then, Raman analysis was used to investigate and form a diamond-like carbon coating. The morphology and surface roughness of the coating were investigated using field emission scanning electron microscopy (FE-SEM) and atomic force microscopy (AFM). The bioactivity behavior of the coating was evaluated by immersion in SBF solution. Table 1 shows the composition of SBF solution

Ion	Concentration (mmol/dm³)	
	Simulated body fluid (SBF)	Human blood plasma
Na^+	142.0	142.0
K^+	5.0	5.0
Mg^{2+}	1.5	1.5
Ca^{2+}	2.5	2.5
Cl^-	147.8	103.0
HCO_3^-	4.2	27.0
HPO_4^{2-}	1.0	1.0
SO_4^{2-}	0.5	0.5

Table 1. composition of SBF solution(8).

3. Results and Discussion

3.1. Raman analysis results

One of the methods to investigate the structural characteristics of diamond-like carbon coatings is Raman analysis. In this analysis, changes in crystalline order in amorphous carbon coatings are expressed according to the spectrum shape, intensity, and location of D and G peaks. The position and intensity of each of these peaks provide interesting characteristics of the carbon structure. Peak G corresponds to sp^2 bonds in both ring and branch form, while peak D corresponds to interplanar defects in the graphite structure. In the Raman spectrum, due to the greater sensitivity of the analysis to sp^2 bonding sites than sp^3 bonds in amorphous carbon, the reduction of sp^2 bonds is considered a measure for the increase of sp^3 bonds [5]. Figure 2 shows the spectrum of Raman analysis of the diamond-like carbon coating.

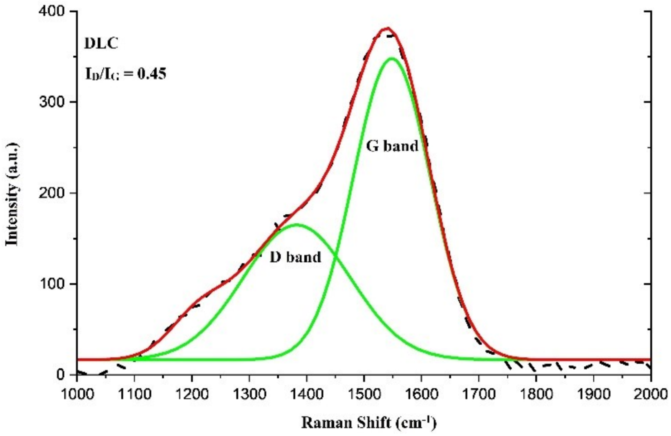


Fig 2- Raman spectrum of diamond-like carbon (DLC) coating.

Raman spectrum curve was fitted using the Lorentz function and two peaks G and D were separated from each other. The Raman spectrum obtained from the carbon coating shows 2 peaks G and D, which indicate the formation of diamond-like carbon. Also, the size of the I_D/I_G ratio in the resulting Raman spectrum is equal to 0.45, which shows a low number in the spectrum of carbon coatings [9]. This indicates that the pseudo-diamond characteristics are high in the coating created by the ion beam process. The low I_D/I_G ratio indicates the existence of many chain groups, which is accompanied by an increase in the amount of sp^3 bonds [9,10].

3.2. results of FESEM and AFM analysis

FESEM and AFM microscopes have been used to examine the morphology and surface roughness of the created diamond-like carbon coating, and the results are shown in Figure 3. The results of the FESEM analysis of the DLC coating surface showed the creation of a uniform, continuous and crack-free coating. The surface roughness of the DLC coating created by AFM analysis was equal to Ra = 4 nm, which indicates that the coating is polished. The level of surface roughness of the layers can predict the reaction of the surface with its surrounding environment, so the higher the level of surface roughness, the greater the amount of friction, damage, and destructibility [11].

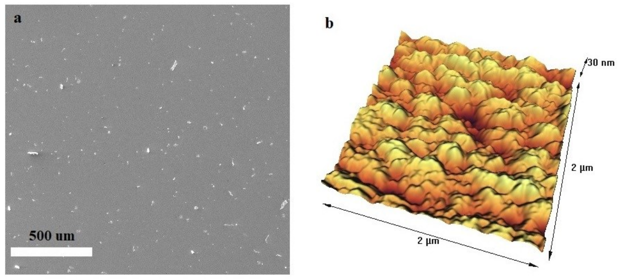
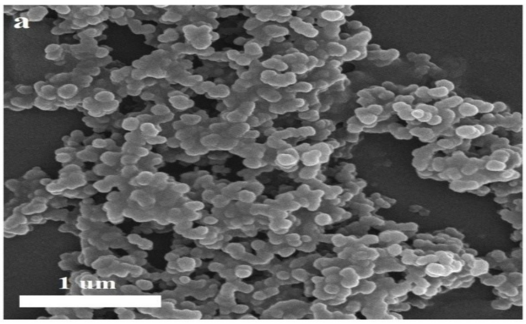


Fig 3- Images of the diamond-like carbon coating surface a) FESEM, b) AFM.

3.3. bioactivity behavior

In order to evaluate the bioactivity performance of the diamond-like carbon coating and to check the ability to form apatite layers, the sample with DLC coating was immersed in the simulated body fluid (SBF) and after 24 hours of immersion, to check the osteogenic performance of the diamond-like carbon coating. FESEM and EDS analysis were used. Figure 4-a shows the formation of biological apatite deposits on the surface of the diamond- like carbon coating after 24 hours of immersion in SBF. This indicates the high bioactivity of the DLC coating. From the deposits formed on the surface of the DLC coating, an EDS analysis was prepared and its results are shown in Figure 3-b. The result of the EDS analysis in Figure 4-b shows the ratio of calcium to phosphorus close to 1.6, which indicates that its ratio is close to the hydroxyapatite phase [12]. Li and his colleagues investigated the biological behavior of bioactive coatings in the SBF environment. They proposed the formation of a double layer in the common chapter of the coating and the SBF environment. The bioactive surface, when it is placed in SBF, during ion exchanges between the coating and the solution, it becomes negatively pregnant. The negatively charged surface causes dissolved Ca^{2+} ions to accumulate in the common phase. As the amount of Ca accumulation depends on the intensity of the negative charge on the surface. The solution becomes saturated around the negatively charged surface and due to the stability of the Hydroxyapatite phase Compared to other calcium phosphate phases, the formation of apatite precipitation from P and Ca ions in the interface gives [3].



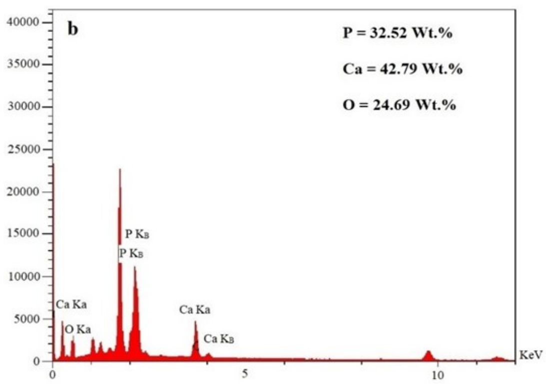


Fig 4. a) FESEM image of apatite deposits formed on DLC coating surface and b) EDS analysis.

4. Conclusion

In this research, the diamond-like carbon coating was created by the ion beam deposition process. Then its structure and bioactivity were evaluated. The general results of the research are as follows:

1- The results of Raman analysis showed the formation of diamond-like carbon coating by the ion beam deposition process.

2- The results of FESEM and AFM analyses showed the formation of a uniform, dense and crack-free coating with very low surface roughness.

3- The results of evaluating the bioactivity behavior of diamond-like carbon coating in SBF solution by FESEM and EDS showed the formation of apatite deposits and the high biocompatibility of the coating.

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