Investigation of Nitrogen-Doped Amorphous Carbon Nanofilms on Magnesium Alloys: A Study of Chemical Characteristics, Microstructural Analysis, Corrosion Behavior, and Biocompatibility

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1. Introduction

Magnesium and its alloys are gaining increasing recognition in the biomedical sector due to their biodegradability, eliminating the need for a secondary surgical procedure to remove implants. Their physical properties, such as an elastic modulus ranging from 41 to 45 GPa and a density between 1.74 and 2.0 $g \cdot cm^{-3}$, closely resemble those of natural bone (3–20 GPa, 1.8–2.1 $g \cdot cm^{-3}$), which helps to reduce stress shielding effects often associated with conventional implants. In contrast to other biomaterials like stainless steel (200 GPa, 8.0 $g \cdot cm^{-3}$) and titanium alloys (103–110 GPa, 8.3–9.2 $g \cdot cm^{-3}$), magnesium alloys offer a more favorable mechanical profile [1-3].

The human body contains between 20 and 28 g of magnesium, with a recommended daily intake of 300–400 mg for healthy adults. While magnesium is essential for numerous cellular functions, its vulnerability to corrosion in moist environments presents considerable challenges. This corrosion can result in mechanical failure and inflammation due to the buildup of hydrogen gas during degradation. To improve corrosion resistance, techniques such as alloying, heat treatment, and especially surface modification have been utilized.

Nitrogen-doped amorphous carbon coatings, recognized for their exceptional wear resistance, impressive hardness, and biocompatibility, can further enhance the performance of magnesium alloys. Studies have indicated that these coatings not only improve mechanical properties but also enhance corrosion resistance, making them particularly appropriate for medical implants. The magnesium alloy (Mg-Zn-Ca), notable for its high strength and ductility, has been effectively used in clinical applications and demonstrates significant improvements in corrosion performance when extruded. Therefore, the integration of magnesium alloys and coatings offers a promising pathway for the development of efficient and safe biomedical implants [3-6].

2. Result and discussion

The alloy was polished, and after polishing and cleaning its surface, the film was transferred onto it. This study presents and examines the use of a nitrogen-doped amorphous carbon (a-C) thin layer over a magnesium alloy (Mg-0.52Zn-0.21Ca), which is ultrathin, ultrasmooth, and corrosion-resistant. A polymer composite based on branched polyethyleneimine was used to synthesize the a-C film, which was subsequently applied to the magnesium alloy surface to enhance its corrosion resistance.

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The amorphous nature of the synthesized film was confirmed through comprehensive characterization using multiple techniques, including XPS, Raman spectroscopy, TEM, and PXRD. Electrochemical workstation analysis, supported by AFM studies and electrochemical corrosion experiments, demonstrated that the synthesized a-C coating significantly improves corrosion resistance and reduces the corrosion rate, as shown in Figure 1a-b.

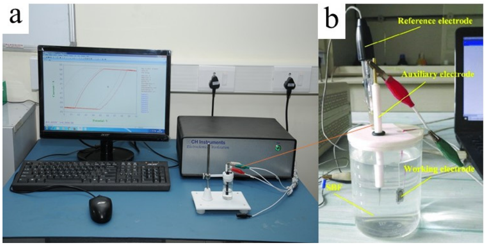

Figure 1. Utilisation of electrochemical workstation for corrosion measurement: (a) electrochemical workstation (b) demonstration of the connection setup for corrosion measurement

Additionally, cytotoxicity tests confirmed the film's non-toxicity and its suitability for orthopedic implant applications, increasing the potential clinical relevance of magnesium-based implants. As a biocompatible and inert nonmetallic element, carbon—when doped with nitrogen—serves as an excellent choice for enhancing both the corrosion resistance and biocompatibility of magnesium-based implants.

The potentiodynamic polarization tests were conducted at a scan rate of 1 mV/s, covering a potential range from −0.4 V to 0.4 V. To assess the corrosion rate, hydrogen evolution was measured through immersion tests. Five uncoated sides of the samples were sealed with silicone rubber to prevent corrosion. All samples were evaluated in modified simulated body fluid (m-SBF) at a temperature of 25 ±1°C.

The behavior of magnesium alloys during anodic polarization is complex due to simultaneous magnesium dissolution and hydrogen evolution, rendering the anodic Tafel slope less informative. Nonetheless, the Tafel extrapolation method can effectively differentiate between samples by examining variations in corrosion current density (I_{corr}) and corrosion potential (E_{corr}). Additionally, the polarization resistance (R_p) can be determined using the Stern-Geary equation, which shows an inverse relationship with Icorr (Table 1).

$$R_p = \frac{\beta_a \times \beta_c}{2.303 I_{corr}(\beta_a + \beta_c)} \tag{1}$$

where β_a and β_c represent the anodic and cathodic Tafel slopes, respectively.

Table 1. Potentiodynamic polarization data of the substrate and a-C coating

Sample	Ecorr (VSCE)	Icorr ($\mu A \cdot cm^{-2}$)	βa ($V \cdot dec^{-1}$)	βc ($V \cdot dec^{-1}$)	RP ($\Omega \cdot cm^2$)
Alloy	-1.77	36.87	0.24	-0.17	1230
Coated Surface	-1.63	15.21	0.22	-0.20	2304

3. Conclusion

The study shows the application of a nitrogen-doped amorphous carbon (a-C) thin nano film on magnesium alloy (Mg-Zn-Ca) to enhance corrosion resistance and biocompatibility for orthopedic implants. After polishing and cleaning the alloy surface, the a-C film, synthesized by using a polymer composite based on branching polyethyleneimine, was applied, resulting in an ultrathin and ultrasmooth deposition. Characterization techniques such as XPS, Raman spectroscopy, TEM, and PXRD confirmed the amorphous nature of the coating. The electrochemical analysis reported that the synthesized a-C coating significantly reduces the corrosion rate. Additionally, cytotoxicity tests confirmed the film is non-toxic, proving its suitability for clinical applications. a-C film, being biocompatible and inert, shows to be an effective material for improving the performance of magnesium-based implants, paving the way for safer and more effective orthopedic solutions.

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