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Mechanical behavior and electrochemical stability of gas-nitrided FeMnAlC alloy in simulated body fluid

Shun-Jen Hsueh [a], Jhen-Yi Huang [a], Chuen-Guang Chao [a], Jenh-Yih Juang [b], Tzeng-Feng Liu [a,*]

[a] *Department of Materials Science and Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 30010, Taiwan*
[b] *Department of Electrophysics, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 30010, Taiwan*

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ABSTRACT

The mechanical performance and electrochemical stability in simulated body fluid (SBF) of a lightweight Fe-30Mn-10Al-1C (in wt.%) alloy after gas nitridation were investigated. The gas nitriding process was performed at 550 °C for 5 h under pure NH_3 atmosphere. The nitrided layer was ~45 μm-thick and consisted predominantly of fine AlN. The surface microhardness, ultimate tensile strength, yield strength, and elongation of the present gas-nitrided alloy are 1814 Hv, 1078 MPa, 1024 MPa, and 77%, respectively. The corrosion tests in SBF showed that the gas-nitrided alloy exhibited a corrosion current density (I_{corr}) of 5.0×10^{-9} A/cm^2, a pitting corrosion current density (I_{pit}) of 5.1×10^{-7} A/cm^2, and a passivation region with ΔE ($\equiv E_p - E_{corr}$) ≈ +1804 mV, respectively, which are substantially better than those obtained in the plasma-nitrided and hydroxyapatite-coated 316L stainless steel. The results demonstrated that the present gas-nitrided alloy having an excellent combination of strength, ductility and corrosion resistance is a promising candidate to replace 316L stainless steel for medical implants.

1. Introduction

316L stainless steel (SS) has been widely used as medical implants due to its good corrosion resistance and mechanical properties [1–3]. However, the metallic implants in constant contact with aggressive body fluids often lead to premature failure. It has been reported that more than 90% of the 316L SS implant devices failed due to significant localized corrosion attack such as pitting and crevice corrosion [4]. Moreover, the metallic ions leaching away from the implants due to corrosion could further result in adverse biological reactions. For example, Fe, Cr and Ni ions released from the corroded 316L SS have been identified as powerful allergens and carcinogens [5–7]. Thus, various surface modification techniques, such as plasma nitriding and hydroxyapatite (HA) coating, have been practiced to improve the corrosion resistance, hence, the biocompatibility and acceptability of the 316L SS implants. In particular, HA coating often plays the role of minimizing the release of metal ions, making the surface more bioactive and stimulating bone growth [5]. Unfortunately, HA is also prone to cracking due to its brittleness and weak tensile strength, resulting in low mechanical reliability [6].

The austenitic FeMnAlC alloys having an excellent combination of strength and ductility are promising materials for a wide variety of lightweight structural applications, including medical implants [8–10]. The density of the FeMnAlC alloy is 6.7 g/cm^3, comparing to that of the 316L SS (7.9 g/cm^3). Previous studies have demonstrated that the corrosion resistance of the plasma- and gas-nitrided FeMnAlC alloys in 3.5% NaCl solution is far superior to those obtained for the nitrided martensitic and precipitation-hardened SS [8–10]. However, the electrochemical stability and corrosion resistance of the nitrided FeMnAlC alloys in simulated body fluid (SBF) has not been investigated yet. This work aims to investigate the mechanical performance and electrochemical stability in SBF environment of the gas-nitrided FeMnAlC alloy.

2. Material and methods

The Fe-30Mn-10Al-1C (in wt.%) alloy used in this study was prepared following the procedures reported previously [9,10]. The gas nitriding was carried out at 550 °C for 5 h under pure NH_3 atmosphere. The surface and cross-sectional morphologies of the gas-nitrided alloy before and after corrosion test were investigated by scanning electron microscopy (SEM, JOEL-6500). X-ray diffraction (XRD) was carried out on a Bruker D8 diffractometer with Cu-Kα radiation (λ = 0.154 nm) to identify the phases in the nitrided layer. The nitrogen concentration and microhardness of

* Corresponding author.
E-mail address: tfliu@g2.nctu.edu.tw (T.-F. Liu).

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the gas-nitrided alloy were determined using glow discharge spectrometer (GDS) and Vicker's indenter with a loading of 100 gf, respectively. The SBF used in this study comprises 8.035 g/L NaCl, 0.225 g/L KCl, 0.355 g/L Na_2HCO_3, 0.321 g/L K_2HPO_4 $3H_2O$, 0.311 g/L $MgCl_2$ $6H_2O$, 0.291 g/L $CaCl_2$, 0.072 g/L Na_2SO_4 and 6.118 g/L TRIS. The nitrided samples were cleaned with acetone and the sample edges were protected with corrosion-resistant plastic tape leaving only ~1 cm^2 exposed to the SBF at 310 K (37 °C) in subsequent potentiodynamic polarization measurements (EG&G Princeton Applied Research model 273). During the polarization measurements, a saturated calomel electrode (SCE) and a platinum foil were used as the reference and auxiliary electrodes, respectively. The dynamical polarization curves were obtained with a scanning speed of 1 mV/sec and a scanning range of −1.2 V to +3.5 V.

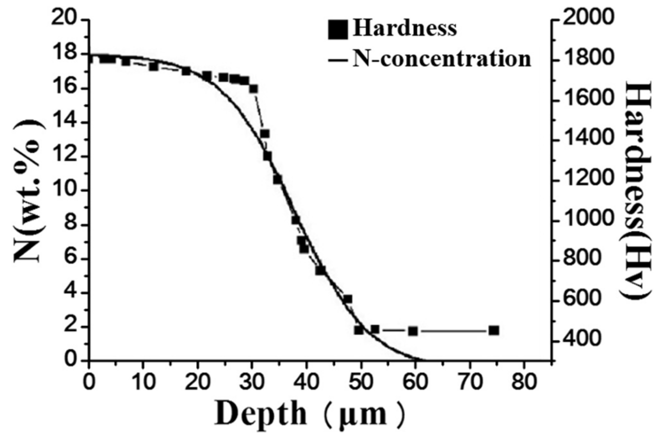

Fig. 2. The depth-dependence of the nitrogen concentration and microhardness of the present gas-nitrided alloy.

3. Results and discussion

Fig. 1(a) is the cross-sectional SEM image of the present gas-nitrided alloy, showing that the nitrided layer is ~45 μm-thick. The XRD result displayed in Fig. 1(b) shows that the nitrided layer is composed predominantly of crystalline AlN. It is noted that the AlN obtained here has the same face-centered cubic (FCC) crystal structure as the austenite (γ) matrix. As shown in Fig. 1(c), the surface morphology reveals that the nitrided layer is consisting of predominantly very dense nano-sized (~190 nm) AlN particles.

Fig. 2 shows the depth-dependence of nitrogen concentration (solid curve) and microhardness (solid square symbols) of the present gas-nitrided alloy. The results indicate that the microhardness is intimately correlated with the nitrogen concentration. The nitrogen concentration at the surface is about 17.9 wt% (43.3 at.%) with a microhardness of 1814 Hv, and both exhibit an apparent plateau within the first several tens of μm. The nearly 50 at.% of nitrogen atomic ratio further confirms that the primary constituent of the nitrided layer is AlN, instead of Fe_4N and/or Fe_3N typically found in the nitrided SS. Since the hardness of AlN (~25.7 GPa) is much higher than that of Fe_3N (11.2–12.4 GPa), and Fe_4N (8.6–11.2 GPa) [9], as a result, the surface hardness of the present nitrided alloy is substantially higher than that of the nitrided 316L SS

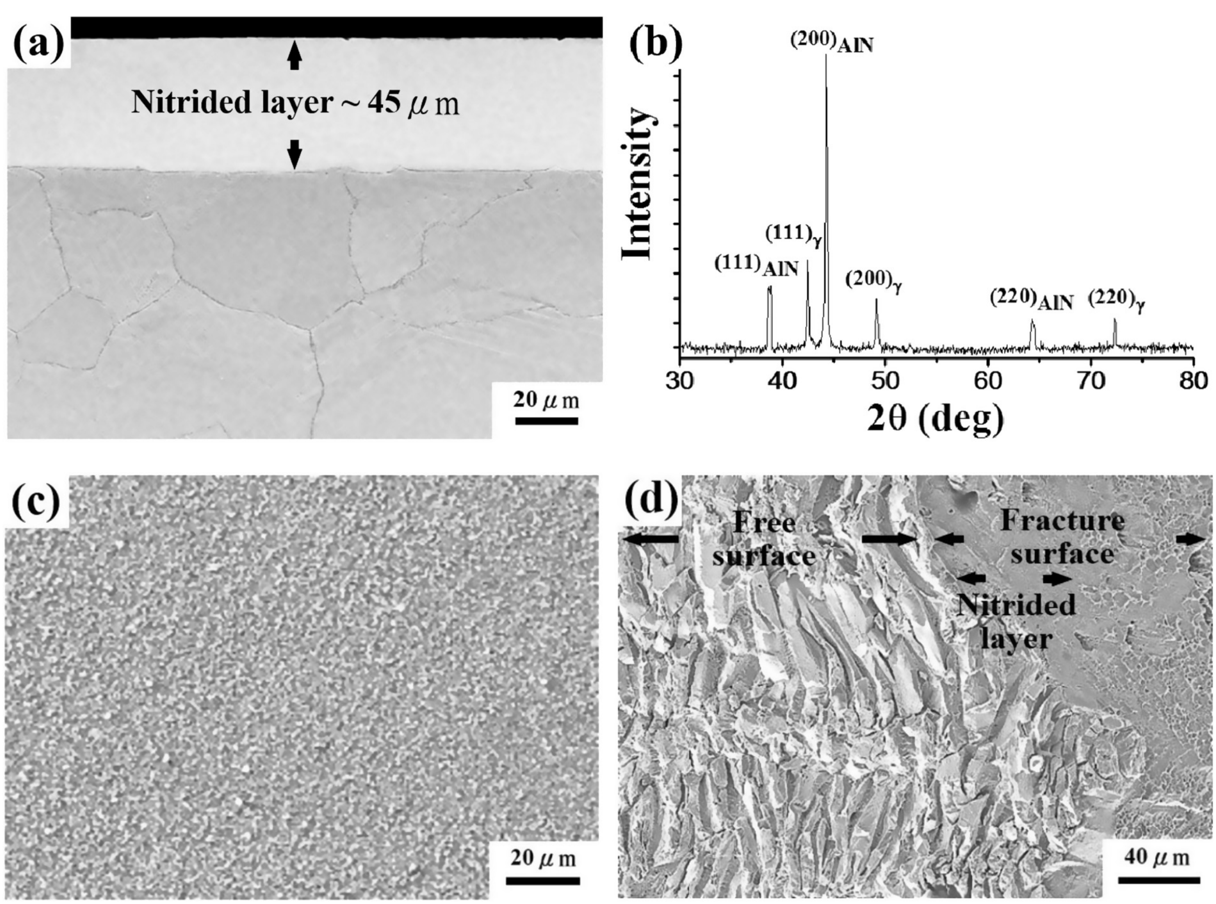

Fig. 1. (a) The cross-sectional structure, (b) X-ray diffraction pattern, (c) the surface microstructure, and (d) the fracture morphology after tensile test of the gas-nitrided alloy.