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Pitting corrosion resistance of La added 316L stainless steel in simulated body fluids

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Abstract

Lanthanum (La), a rare earth element with anticoagulative and antiphlogistic function, was added into the medical grade 316L stainless steel in order to improve its biocompatibility. The corrosion resistance of the La added 316L steel in two different simulated body fluids, simulated blood plasma and Hank's solution, was evaluated. The result showed that the addition of La in the steel could largely affect the corrosion behavior of the steel. The steel with 0.01% La showed the widest passive region and the best resistance to pitting attack, within the addition range of La from 0.01% to 0.08%. The corrosion resistance improvement of La added 316L stainless steel is probably due to the effect of La on the purification of the steel, the modification of inclusions, and the passive film formation in the simulated body fluids.

Keywords: Corrosion; 316L; La; Pitting

1. Introduction

316L austenitic stainless steel is used as implant materials to make such devices as artificial joints, bone plates, stents and so on, thanks to its favorable combination of mechanical properties, corrosion resistance, satisfactory biocompatibility and relatively low cost compared with other metallic biomaterials [1]. However, after its implantation in human bodies, sometimes mechanical failure occurs and tissue inflammation may happen, which makes safety become dissatisfactory and insufficient for its biomedical applications [2].

Because of the high concentration of Cl^- and the temperature range of 36.7–37.2 °C, the human body fluid is considered a severely corrosive environment and localized corrosions such as pitting, crevice corrosion and fretting fatigue are probable to appear on 316L steel [3]. Metal ions such as iron, chromium and especially nickel could be released and thus cause toxicity to the body and deteriorate the 316L biocompatibility [4–6]. Therefore, improvement of the biocompatibility of 316L steel, especially its blood compatibility when used in the vascular environment, can be beneficial to its safe use in the human body.

Lanthanum (La) is a rare earth element, which possesses biological effects such as antitumour, anticancer and anticoagulants, and is considered to be nontoxic with appropriate concentration or dosage [7–9]. In order to further improve the blood compatibility of 316L steel, La was added into the steel in the present work. Moreover, the corrosion resistance should be studied because of its importance for biomedical applications. In this study, the potentiodynamic polarization tests in different simulated body fluids (SBF) at 37 °C were performed to evaluate the corrosion behavior of the La added 316L steels.

2. Experimental

2.1. Specimens

Medical standard 316L stainless steels with different La addition were prepared by vacuum induction melting with pure metals of iron, chromium, nickel, molybdenum and lanthanum. The steel ingots were hot forged into plates with thickness of

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Table 1
Chemical compositions of medical 316L stainless steels with La additions/wt.%

Steels	C	Cr	Ni	Mn	Mo	Si	S	P	La
316L	0.025	17.5	13.0	1.06	2.66	0.60	0.008	0.023	–
0.01% La	0.020	17.5	13.7	0.93	2.95	0.51	0.003	0.010	0.007
0.04% La	0.016	17.3	13.6	1.11	2.96	0.44	0.003	0.010	0.040
0.08% La	0.010	17.2	13.6	1.52	2.83	0.62	0.003	0.009	0.083

about 16 mm. A medical grade 316L stainless steel was also obtained by the same procedure. The chemical compositions of these steels are listed in Table 1. Specimens with the size of 1 cm × 1 cm × 0.7 cm were cut, solution treated at 1050 °C for 0.5 h and water quenched, and then coated with epoxy resin except for a measurement area of 1 cm^2. The coated specimens were ground with a series of SiC papers and mechanically polished to minor finish, then degreased in acetone and washed with distilled water. Before polarization, all the specimens were ultrasonically rinsed in ethanol for 5 min.

2.2. Electrolytes

The SBF used in this study were the simulated blood plasma and Hank's solution that were prepared by mixing the analytical grade reagents and distilled water, with pH value of 7.4 ± 0.2. Compositions of the SBF are listed in Table 2. The electrolyte of about 500 mL without deaeration was used and maintained at 37 ± 1 °C open to air by a water-bath throughout the whole investigations.

2.3. Polarization

A three-electrode system with a saturated calomel electrode (SCE) as the reference electrode and a platinum plate as the counter electrode was used to conduct the electrochemical tests, and all the potentials in this study were versus SCE. The electrochemical workstation CHI660A that is controlled by a computer was used to measure the polarization curves of the steels. Before the electrochemical measurement, the specimen was immersed into the solution for about 30 min to make its open-circuit potential (E_{ocp}) become stabilized, and then the potentiodynamic polarization with a scan rate of 0.3 mV/s was carried out from the potential of −0.4 V or −0.5 V, which was below E_{ocp}, to

Table 2
Compositions of SBF/g/L [10,11]

Components	Simulated blood plasma	Hank's solution
NaCl	6.80	8.00
KCl	0.40	0.40
$CaCl_2$	0.20	0.14
$NaHCO_3$	2.20	0.35
$MgSO_4 \cdot 7H_2O$	0.20	0.06
Na_2HPO_4	0.13	–
$NaH_2PO_4 \cdot 2H_2O$	0.03	–
$MgCl_2 \cdot 6H_2O$	–	0.10
$Na_2HPO_4 \cdot 12H_2O$	–	0.06
KH_2PO_4	–	0.06
D-glucose	–	1.00

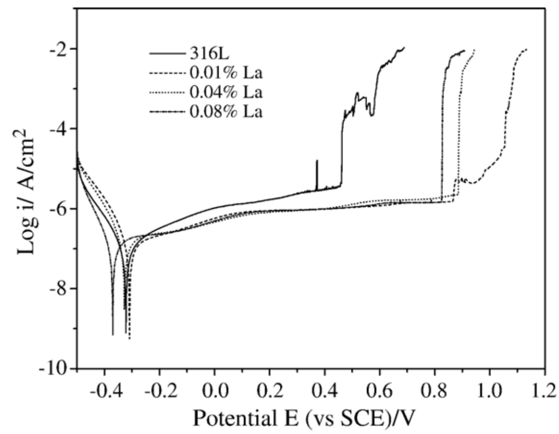

Fig. 1. Polarization curves of the La added stainless steels in simulated blood plasma at 37 °C.

the potential with the current density of about 0.01 A/cm^2. All the measurements were repeated at least three times, and a new solution was used if a new polarization test was performed.

3. Results and discussion

Figs. 1 and 2 show the potentiodynamic polarization curves of the La added medical 316L stainless steels at 37 °C in the simulated blood plasma and Hank's solution, respectively, from which both the anodic and cathodic parts can be seen clearly. These two figures show that the polarization currents are significantly low before the pitting occurs, and then the currents suddenly increase to a high level.

All the steels have shown evident passive characteristics in the two tested solutions. Passive current densities of the La added 316L steels were around 1 μA/cm^2 or lower while those of 316L steel were higher than 1 μA/cm^2 and increasing with the increase of potential in anodic polarization. Moreover, it can be seen from Fig. 3 that the pitting potentials of the La added 316L steels are all higher than that of 316L steel in both solutions, which indicates that all the La added steels are more corrosion resistant than 316L steel. A significantly different behavior of La added 316L steel has been observed in 0.9% NaCl physiological solution where only the steel containing 0.01% La has shown to be more corrosion resistant than the 316L steel while the 0.04% and 0.08% La steels have shown to be equally and less corrosion resistant than the 316L steel, respectively [12]. In the present

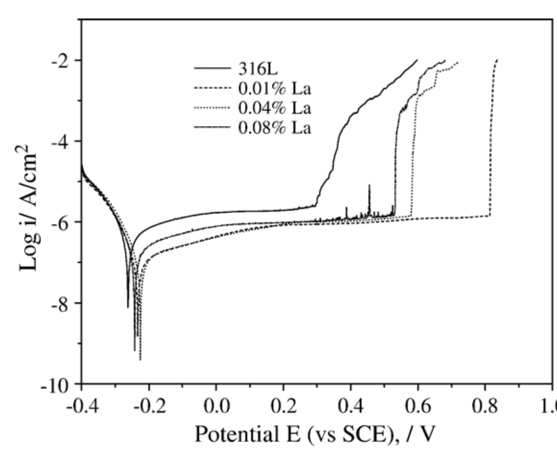

Fig. 2. Polarization curves of the La added stainless steels in Hank's solution at 37 °C.