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Poster Oral

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Corrosion behavior of NdFeB permanent magnet in two neutral environments

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Abstract

The NdFeB uncoated magnets have been magnetically characterized by demagnetization curves and their corrosion behavior have been evaluated (nonmagnetized state) by accelerated, immersion and electrochemical corrosion tests. The hydrothermal corrosion resistance was evaluated by: high accelerated stress test (HAST) and bulk corrosion test (BCT). The immersion tests were performed in ultrapure water with or without addition of chloride ions. The electrochemical tests, open circuit potential (OPC) and electrochemical impedance spectroscopy (EIS) were carried out in two neutral solutions (NaCl and Na₂SO₄), and on the two distinct surfaces of cubic magnets, i.e. parallel and perpendicular (pole) to the crystallographic *c*-axis of aligned ferromagnetic grains. Both accelerated tests presented weight loss below 1.0 mg/cm² (BCT grade A). The chloride ions additions in immersion tests caused differential aeration corrosion. The EIS tests carried out in NaCl solution were more aggressive than in Na₂SO₄ solution, and indicated a different corrosion behavior between the parallel and pole faces evidenced by the response of the Nyquist diagrams.

Keywords: NdFeB, corrosion, permanent magnet, BCT, HAST, EIS

Introduction

The high performance magnets have been widely applied in different industrial fields. Sintered NdFeB magnets exhibit excellent magnetic properties, energy product (HB_{max}), and coercivity (iH_c) (1), nevertheless, in spite of technological advances regarding chemical composition and microstructure controlling have been reached, these magnets still presents poor corrosion resistance and limited thermal stability (2). The aim of the present work was to study the corrosion behavior by accelerated tests and the role of chloride and sulfate solutions in the EIS tests.

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Methodology

The equipment of Laboratorio Elettrofisico model IS-300 was used for the magnetic characterization of the magnets. Accelerated tests HAST and BCT were performed in an ESPEC chamber, model EHS-212M. For hygrothermal corrosion resistance evaluation the weight loss was determined according to ASTM A1071/A1071M-11(3). The Immersion tests were performed in two media: in ultrapure water obtained by reverse osmosis and in 0.05 mol.L^{-1} NaCl solution (both at pH ~ 7.0). At the end of tests the samples were pickled during 10 seconds in Clark's solution. The electrochemical tests were carried out using a potentiostat/gavanostat model VersaSTAT3 from PAR. The sequence of OCP (18h) measurements and EIS tests was performed with two different electrolytes: 0.5 mol.L^{-1} of Na_2SO_4 and 0.15 mol.L^{-1} of NaCl, using a three-electrode cell arrangement. All tests were performed in uncoated samples, nonmagnetized state, and naturally aerated quiescent solution.

Results and discussion

The magnetic properties, energy density, intrinsic coercivity and remanence ($\text{BH}_{\text{max}} = 336.6 \pm 6.7 \text{ kJ/m}^3$; $H_{\text{c}j} = 145 \pm 21 \text{ kA/m}$; $B_r = 1.314 \pm 0.013 \text{ T}$) obtained as results from demagnetization curve allowed to categorize the studied magnets as N42. Table 1 presents the weight loss and corrosion rate of HAST (130 °C and 95 % relative humidity (RH)) and BCT (120 °C and 100 % RH with condensation) tests after 4 and 7 days, respectively. Figure 1 presents the samples images after the end of HAST (a) and BCT (b) tests.

Table 1 - Weight loss and corrosion rate of BCT and HAST tests.

Tests	Duration of test	Weight Loss (mg/cm^2)	Corrosion rate (mmy)
HAST	96 hours (4 days)	0.009 ± 0.001	0.0011 ± 0.0002
BCT	168 hours (7 days)	0.27 ± 0.14	0.018 ± 0.009

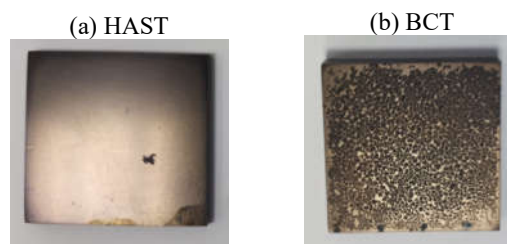


Figure 1 – Magnets images after (a) HAST and (b) BCT tests.

The weight loss and corrosion rate of samples after 5 days of immersion in ultrapure water (pH ~ 7.0) with or without addition of 0.05 mol.L^{-1} NaCl solution are presented in Table 2. Figure 2 presents sample images after the end of immersion test, (a) ultrapure water and (b) ultrapure water with chloride ions.

Table 2 – Weight loss and corrosion rate of immersion tests

Tests	Duration of test	Weight Loss (mg/cm^2)	Corrosion rate (mmy)
Immersion H_2O : ultrapure	120 hours (5 days)	1.09 ± 0.03	0.10 ± 0.01
Immersion $\text{H}_2\text{O} + \text{NaCl}$	120 hours (5 days)	1.87 ± 0.08	0.17 ± 0.01

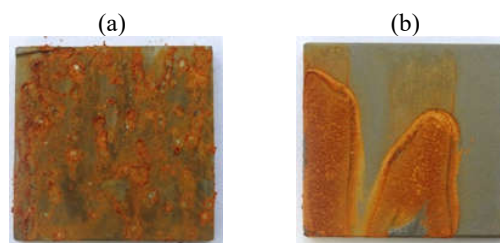


Figure 2 – Magnets images after 5 days of immersion: (a) ultrapure water, (b) with chloride ions (0.05 mol.L^{-1} NaCl solution).

The HAST test, which does not generate condensation of the water vapor, was less aggressive in comparison with BCT test with water vapor condensation. The ASTM A1071/A1071M-11 categorizes the magnets that were exposed to standard BCT test conditions (exposure time: 4 days) in 6 grades. Even after 7 days of test duration, the magnets were still categorized in BCT grade A, presenting weight loss less than 1.0 mg/cm^2 , i.e. in the highest category to hydrothermal corrosion resistance. As shown in Table 2, the corrosion rate of magnets in immersion with chloride ions addition was about two times higher than that calculated for ultrapure water. At the end of immersion test, the samples showed different corroded areas, as can be seen in Figure 2. The ultrapure water caused general corrosion on the magnet surface, while the medium with chloride additions promoted a clear a separation of anodic and cathodic regions. These phenomena can be explained by the oxygen transport on the magnet surface, i.e., by differential aeration corrosion (4). Figure 3 presents EIS diagrams, Nyquist (a) and Bode (b), for the parallel and pole faces in the sulfate and chloride sodium solutions.

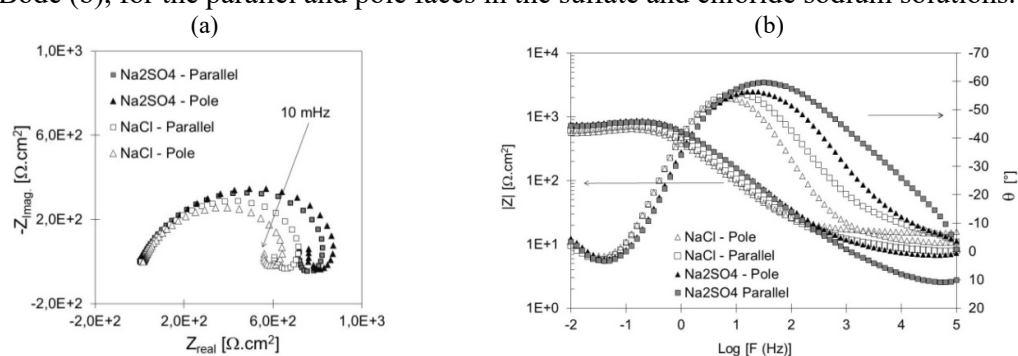


Figure 3 - EIS diagrams, (a) Nyquist and (b) Bode, after 18 hours for the parallel and pole faces in naturally aerated solutions, $0.5 \text{ mol/L Na}_2\text{SO}_4$ and 0.15 mol/L NaCl , $\text{pH} \sim 7.0$.

The Nyquist diagrams show at least two time constants, one capacitive at high-to-medium frequencies and another inductive at lower frequencies. The capacitive loops indicate that chloride was more aggressive than sulfate solutions. After 18 hours of exposure, parallel and pole faces showed similar global impedance values for all condition evaluated (Figure 3b).

Conclusions

The water vapor condensation in BCT test intensifies the corrosion process of magnets in comparison with HAST test. The immersion tests presented differential aeration corrosion for sodium chloride medium. The EIS tests showed that the sodium chloride medium was the most aggressive and indicated a slight difference in the corrosion behavior between parallel and pole faces. Pole face was slightly more susceptible to corrosion in chloride medium than parallel faces.

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