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Investigation of magnetic, mechanical and microfailure behavior of ARMCO-type low carbon steel corroded in 3.5% NaCl-aqueous solution

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ABSTRACT

The corrosion effects of 3.5% NaCl aqueous solution on the tensile mechanical, micromagnetic Barkhausen emission (MBE) and microfailure behavior of low carbon steel were investigated. At first it was found that this steel shows a dramatic and consistent decrease of its ductility with time of corrosion. The ductility reduction as well as microfailure features obtained by Scanning Electron Microscopy (SEM)-fractographic analysis yields an acceptable evidence for the occurrence of the Hydrogen Environmental Embrittlement (HEE) phenomenon during the corrosion process.

During tensile straining the MBE-signal increases monotically at an average constant rate towards necking point. This rate shows tendency to increase with corrosion time fact which helped to establish the existence of a corrosion-induced micromagnetic hardening rate effect. It was shown that the main contribution to this effect should be attributed primarily to the combined effect of the HEE and dislocation multiplication and to a lower extent to the formed magnetite (Fe_3O_4) surface layers. Necking plasticity and MBE were correlated on the basis of combined stress bias and microvoid/microcracking-induced creation and rearangement of magnetic domains.

1. Introduction

It is known that the corrosion products of steel and iron consist of ferric oxy-hydroxides (α-, β-, and γ-FeO(OH), magnetite (Fe_3O_4) and amorphous iron oxide. The content of these materials in the formed rust is dependent upon the corrosion condition. The formation of magnetite by reactions of α-, β- and γ-FeO(OH) phases with ferrous species in aqueous media, i.e. the transformation mechanisms of FeO(OH) to Fe_3O_4 (magnetite) are rather complex [1–4].

The corrosion products of steel and iron in an environment with Cl^- contain more magnetite than products in absence of Cl^-. However, the corrosion of steel and iron generally occurs in the presence of O_2 and there are, for example, sea water conditions where the magnetite can easily be formed by oxidation of ferrous species in the presence of Cl^-.

Sea water is a complex chemical system defined by various factors such as concentration of dissolved oxygen, conductivity, salinity, biological activity etc. All these factors participate in a delicate balance in the natural environment.

The corrosive behavior of stored seawater is differentiated from that of natural seawater because this balance gradually changes. As a result seawater is not easily simulated in laboratory scale experiments for corrosion-controlling purposes. On the other hand the existing synthetic seawater (MBL, ASTMD 1141) has much more complex composition than 3.5% NaCl solution and may be less effective for quick and adequate simulation of natural sea-water behavior. For this reasons a 3.5% NaCl–water solution was preferred to be used since it is known that it is more aggressive for the low-carbon steel than the natural and synthetic seawater.

Low carbon-high strength low alloy (HSLA) steel used for marine structures require not only excellent mechanical strength to bear heavy loads but also high corrosion resistance under combined conditions of exposure to seawater, raining and sun-shine. The strength of this steels and other mechanical properties such as necking plastic instability or ultimate yielding among others, are strong related to several microstructural parameters which, for example may be of micromechanical as well as of micromagnetic nature. Such parameters based for example on microfailure and MBE analysis could play an important role in the investigation of such steel under the above mentioned corrosive conditions. In this context it would be of interest, as a first step, to

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have valuable informations gained by experiments concerning the influence of seawater corrosion conditions on these two parameters of a "simple" and relevant "modeling" material such as ARMCO-type low carbon steel. Such information would help to better understand and to explain certain related magnetomechanical properties which are important for the characterization of the corrosion resistance of steels.

Under this point of view experimental investigations concerning the combined effects of corrosion performed in 3.5% NaCl aqueous solution on mechanical, micromagnetic and microfailure behavior of low-carbon steel have probably been very scarcely made and thus could not be found by the authors in the related literature. In this sense the aim of this paper is to try to fill, at least in part, this gap by giving some new insights into the complex influence mechanisms by which certain mechanical, micromechanical as well as micromagnetic properties of low-carbon steel are affected by seawater-type corrosion conditions.

2. Experimental

A block diagram of the experimental set-up used for the measuring the micro-magnetic Barkhausen emission (MBE) parameter is shown in Fig. 1.

A current from a sweep controller circuit was fed to a bipolar high current generator to generate a symmetric bipolar triangular waveform. The amplitude of this waveform is ± 0.4 A which generates a magnetic field of ± 10 kA/m, enough to reach saturation magnetization level of the material. The MBE signal at 10 Hz excitation was acquired by a 2 mm ferrite-cored surface probe which had 1000 turns and was then amplified to 40 dB using a low noise amplifier. The amplified signal was band-pass filtered in the range 500 Hz to 10 KHz for eventual voltage and spectral analysis measurements. The total number of Barkhausen counts (events), the so-called jumpsum, was measured for a period of 1 s using the counter processing module of the given apparatus. An adequate threshold voltage was used to eliminate low-amplitude circuit noise and other background noise. For sake of convenience the waveform of Barkhausen noise was observed with a digital oscilloscope. The chemical composition of the used material is given in Table 1. The material was a polycrystalline one with average grain size of about 25 μm. This material was received in form of sheets produced by cold-rolling and subsequent adequate annealing for stress-relief. The specimen has dog-bone-type geometry where thickness was 2 mm, width 10 mm and the effective gauge length 100 mm. The samples were subjected to uniaxial tensile test at room-temperature and nominal strain rate 2×10^{-3}/min, using a universal testing machine of Instron-type. The ultimate stress was 380 MPa and the yield stress (0.2% off-set) was 190 MPa. Also, the measured hardness was about 115 HV. The specimens were continuously loaded and data were taken at convenient time intervals (on-line loading). The fractured specimens were stored in a desiccant up to the time of SEM examination. This was judged to be necessary in order to avoid any further mechanical and/or chemical damage of fractured surfaces exhibiting microscopically fine details. Otherwise, acquisition of reliable measurements by SEM-fractographic analysis may become a lignеous or even impossible.

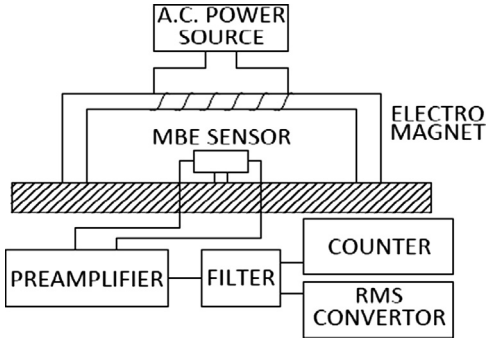

Fig. 1. Block diagram of MBE setup.

Table 1
The chemical composition of ARMCO type steel.

C	Mn	Si	Ni	Cr	Mo	S	P	N
0.04	0.37	0.01	0.017	0.01	0.001	0.014	0.01	0.003

The surface of the specimens were prepared by using 600 grit SiC paper followed by ultrasonic cleaning in pure ethanol and subsequently rinsed by distilled water. The cleaning procedure was performed as quickly as possible to avoid premature corrosion. Thereafter, the samples were exposed to a corrosion environment made of a continuously sprayed 3.5% NaCl aqueous solution in a Salt Spray Fog (SSF) apparatus. The testing apparatus is a cylindrical recipient with dimensions: height about 1 m and diameter 80 cm in which the specimens are placed and continuously sprayed with 3.5% NaCl-solution under controlled pressure. On the bottom of the apparatus there is a transparent cover made of Plexiglas for monitoring the spraying process. All corrosion experiments were performed at room temperature (approximately 25 °C). The exposure time in the SSF apparatus was 200, 400, 600, 800 and 1000 hours. The corrosion product was a brownish, scale-like layer formed on the specimen surface. This was a loosely adhering layer whose components were mainly amorphous oxides and ferric oxyhydroxide of type γ-FeO(OH) (lepidocrocite), which was formed according to the reaction

$$Fe + [O] + OH^- \rightarrow \gamma - FeO(OH) \quad (1)$$

This layer can be easy chipped from the surface revealing underneath a black and strong adhering layer in form of magnetite rust (Fe_3O_4). During the magnetite formation the following reactions may occur [4]:

$$Fe \rightarrow Fe_2^+ + 2e^- \quad (2)$$

$$Fe^{2+} + FeO(OH) \rightarrow Fe_3O_4 + 2H^+ \quad (2a)$$

$$H^+ + e^- \rightarrow H \quad (2b)$$

The non-magnetic γ-FeO(OH) layer and other loosely adhering amorphous iron oxides were removed by dry air blast and soft natural bristle brush.

3. Results and discussion

Fig. 2a shows the stress–strain data obtained by tensile test. A dramatic reduction of the fracture strain (ductility) of the corroded specimens is observed. Specially, the ductility is reduced by about 40% for 1000 h corrosion time. At the same time a tendency of a slight decrease in the tensile strength can be observed. This behavior is indicative of embrittlement of the material [5–7]. By means of this data the plot given in Fig. 2b was obtained which show a linear decrease of the ductility at a constant rate with time of corrosion. In this sense the reduction in ductility is a measure of the degree of the embrittlement.

In Fig. 3 the measured MBE-signal of corroded (rusted), not-strained specimens versus time of corrosion is presented. One can easily observe the formation of two linear ranges of a low increase