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Non-contact, nondestructive hydrogen and microstructural assessment of steel welds

Kamalu Koenig [a,*], Angelique N. Lasseigne [b], Joseph W. Cisler [a], Brajendra Mishra [a], Robert H. King [a], David L. Olson [a]

[a] Colorado School of Mines, MME Dept, 1500 Illinois St, Golden, CO 80401, USA
[b] Generation 2 Materials Technology, LLC, Denver, CO, USA

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ABSTRACT

Nondestructive low-frequency impedance has been developed to determine hydrogen content in operating pipeline steel and weldments through a structural coating. A low frequency impedance measurement is similar to a resistivity measurement with a depth function due to the sensor coil reactance. Resistivity introduces variability in impedance measurements because resistivity is a function of the conductivity of the material, the depth of the measurement, and the alloy content. The conductivity, based on the free electron model, is a function of the electronic effective mass, the electron concentration, and the dominating scattering mechanisms, which is altered by such factors as inclusions, microstructure, temperature, and strain. Each of these variables must be separated out to obtain a hydrogen content measurement in operating pipelines (with a structural coating) using low frequency impedance. Techniques used to separate out the variables associated with operating pipeline steels are presented. The use of real-time low frequency impedance measurements to monitor hydrogen content as it diffuses out of a steel weldment is presented and discussed.

1. Introduction

Pipeline steels are becoming more susceptible to hydrogen damage as the strength of the steel increases. The oil and gas industry are demanding higher strength steels (yield strength of 70 ksi or greater) to be able to operate at higher pressures with larger diameters and smaller wall thickness. Only a few parts per million of hydrogen present in the high strength steel could result in hydrogen damage. A hydrogen tolerance limit has not been determined for the higher strength pipeline steels. The effect of service life makes it even more difficult to predict a single hydrogen content tolerance limit for high strength pipeline steels. It is essential to have a nondestructive means to monitor hydrogen content in high strength pipeline steels and weldments over the life of the pipeline to prevent significant damage or failure.

A nondestructive hydrogen content sensor for field measurements must be able to operate through the pipeline structural coating, which means non-contact and nondestructive technology must be utilized. Low frequency impedance measurements provide an effective non-contact method to determine hydrogen content through a pipeline coating. Low frequency impedance measurements have been correlated to hydrogen content in steel weldments both in the laboratory and in the field. The development of a real-time, nondestructive, non-contact, in-field hydrogen sensor utilizing low frequency impedance is described.

2. Low frequency impedance

In low frequency impedance testing, a low frequency alternating current is passed through a coil of conducting wire. This coil induces a primary magnetic flux that couples with the material being inspected, creating a magnetic circuit. The magnitude of this primary flux is given by Eq. (1).

$$\phi_p(t) = \int B_{coil}(t) \cdot \vec{n}\, da \quad (1)$$

$B_{coil}(t)$, is the oscillating magnetic flux density induced by the coil given by Eq. (2).

$$B_{coil}(t) = \mu_{core} N I(t) \quad (2)$$

μ_{core} is the magnetic permeability of the core material of the coil, N is the number of turns of the wire comprising the coil, and $I(t)$ is

* Corresponding author. Tel.: +1 720 935 8401; fax: +1 303 273 3795.
E-mail address: kkoenig@mines.edu (K. Koenig).

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the amplitude of the applied alternating current. The oscillating nature of the flux induces eddy currents in the sample beneath the coil. The eddy currents produce a secondary flux, which, in accordance with Lenz's law, opposes the primary flux that generated the eddy currents. An equilibrium flux, ϕ_E, is the difference between the primary and secondary fluxes. The coil voltage is a function of this equilibrium flux and is given by Eq. (3).

$$V_{coil}(t) = -N\frac{d\phi_E}{dt} \tag{3}$$

The eddy current interaction with the material being inspected will influence the secondary flux, which in turn influences the equilibrium flux and the coil voltage. Therefore, the coil voltage reflects the total voltage for the entire magnetic circuit. The general form of Ohm's law is given by Eq. (4).

$$V(t) = I(t)Z \tag{4}$$

The total impedance Z, given by Eq. (5), is a combination of the coil resistance, R, and the frequency-dependent reactance of the coil, X.

$$Z = \sqrt{R^2 + X^2} \tag{5}$$

At low frequencies, the reactance term is negligible and impedance is approximated by resistance. The resistance of the magnetic circuit is due to the resistance of the conducting wire of the coil and the eddy current interactions with the inspected material. The eddy current density, which determines the strength of the interaction with the inspected material, is determined by the strength of the induced magnetic field in the material. The ratio of the induced magnetic flux density at some depth B_d, with the magnetic flux density induced at the surface of the inspected material, B_0, is given by Eq. (6).

$$\frac{B_d}{B_0} = \exp\left(-\frac{d}{\delta}\right)\sin\left(wt - \frac{d}{\delta}\right) \tag{6}$$

The standard depth of penetration, δ, is the scaling factor for this equation. It is equal to the depth at which the induced flux density has decayed to approximately thirty-seven percent of the surface value. The standard depth of penetration (in mm) is given by Eq. (7).

$$\delta_{mm} = \frac{50}{\sqrt{f\mu_r\sigma}} \tag{7}$$

f is the frequency of the applied alternating current in Hz, and σ and μ_r are the conductivity and relative magnetic permeability of the inspected material. [1] A permanent magnetic yoke is used to simulate the magnetic field strength due to magnetic remanence. The increased magnetic field lowers the relative magnetic permeability, μ_r, in the inspected material and increases standard depth of penetration, δ_{mm}, as suggested by Eq. (7). A significant advantage of the low frequency impedance technique is that it can be performed at a coil liftoff distance and through structural coatings.

Fig. 2. Coil encircling an X80 steel laboratory specimen.

Variability in low frequency impedance measurements exists because resistivity is a function of the conductivity of the material, the depth of the measurement, and the alloy content. The conductivity, based on the free electron model, is a function of the electronic effective mass, the electron concentration, and the dominating scattering mechanisms, which is altered by such factors as inclusions, microstructure, temperature, and strain. Each of these variables must be separated out to obtain a hydrogen content measurement using low frequency impedance. All of the controllable parameters are determined to optimally detect the desired material parameter.

3. Laboratory low frequency impedance hydrogen content measurements

The development of a low frequency impedance hydrogen sensor for coated pipeline steel and weldments began in the laboratory. First it was necessary to prove that low frequency impedance could be correlated to hydrogen content in pipeline steel. The low frequency impedance laboratory results for hydrogen content as a function of frequency for hydrogen charged X80 (80 ksi yield strength) pipeline steel is shown in Fig. 1. The cylindrical X80 steel line pipe specimens had total hydrogen contents ranging from 0.78 to 28.4 ppm of hydrogen as determined by the LECO RH-404 Hydrogen Determinator. The RH-404 has a precision of the greater of 0.05 ppm or 2% RSD, for a 1 g sample. However, there are no calibration standards for levels below 1.0 ppm.

The results are most important at lower frequencies (100 Hz) to guarantee a maximum penetration depth of five mm beneath the steel surface. At frequencies beyond 1000 Hz, only skin effects become important and these measurements cannot be attributed to variations in hydrogen content in the steel.

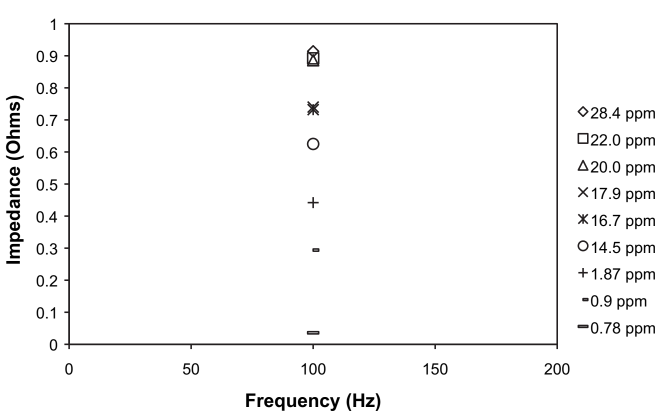

Fig. 1. Frequency sweep of impedance with change in hydrogen content in tin coated hydrogen charged X80 steel specimens [2].

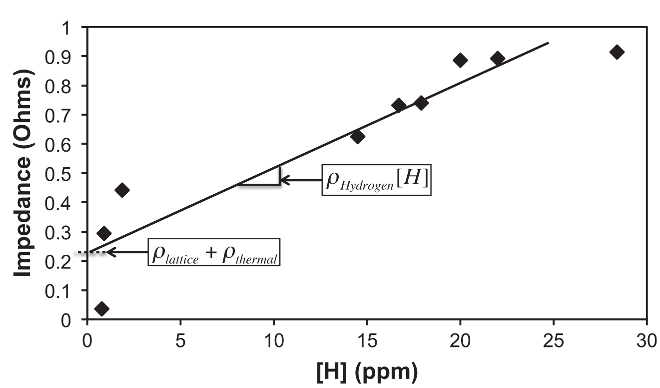

Fig. 3. Impedance measurements as a function of hydrogen content at a frequency of 100 Hz. The resistivity of hydrogen is given by the slope of the line and the y-intercept is the sum of resistivities due to temperature and the lattice [2,4].