Measurement 127 (2018) 98–103

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Novel austenitic steel ageing classification method using eddy current testing and a support vector machine

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ARTICLE INFO

Keywords:
Eddy current method
SVM classification
Aging states
External surface
Heat-resistant austenitic steel

ABSTRACT

This paper describes the development of an original eddy current method for the characterization and classification of different aging states of heat resistant austenitic steel tubes, commonly used in petrochemical industry to produce oil derivatives. These tubes are exposed to high temperatures causing microstructural transformations. They are also under oxidizing environments leading on the formation of an external surface with ferromagnetic behavior. An eddy current testing (with a Hall sensor) was used in order to observe magnetic changes in the specimen. The amplitude and phase-shift of the eddy current signals are calculated and used as features for the samples characterization. An electromagnet was implemented in order to overpass the ferromagnetic external surface and measure the base metal response. A finite element simulation was also developed in order to estimate the skin depth of the eddy currents in samples with different aging states. A machine learning algorithm has been used to classify the test specimen based on the extracted features. Results suggest that the proposed method is a potential non-destructive technique for the characterization and classification of heat-resistant austenitic steel tubes with different aging states.

1. Introduction

Heat-resistant austenitic stainless steel tubes are commonly used in reformer furnaces due to their high mechanical properties, superior strength to creep rupture and good corrosion resistance [1,2]. Reformer tubes are exposed to severe operational conditions that cause the aging phenomenon, creep, carburization, oxidation, thermal shock and accidental overheating. The service life of these tubes is limited by creep damages [3,4]; therefore, the use of non-destructive methods is important in order to overcome unexpected furnace shutdowns. Thus, it is important to evaluate the microstructural evolution of the reformer tubes in order to monitor their structural condition during service [5]. Non-destructive evaluation (NDE) techniques can play an essential role to determine the tube condition. Eddy current testing (ECT) is a reliable NDE method that has been widely used for defects detection, thickness measurement and materials characterization [6]. ECT is based on the Faraday's law of electromagnetic induction. A primary excitation coil is driven by a sinusoidal excitation signal that produces an alternating magnetic field inducing eddy currents in the tested sample. The eddy currents produce a magnetic field that opposes the field of the primary coil [6]. In conventional ECT technique, these field variations can be detected using the same coil that generates the excitation magnetic field by measuring its impedance [6,7]. Magnetic sensors can be used to measure the magnetic field perturbations, such as the Superconducting Quantum Interference Devices (SQUIDS) [8,9], Hall effect sensors [10,11], Anisotropic Magnetoresitors (AMR) and Giant Magnetoresistors (GMR) [12,13]. GMR sensors are more sensitive, they work on a wide bandwidth and their response is practically linear when properly polarized [13–15]. As our tested samples exhibit heterogeneous magnetic response that could change the linear region and saturate the GMR sensor, a Hall sensor was chosen for sensing the eddy current signals. Thus, a Hall effect sensor fulfils all the required features, since it has linear response to an external magnetic field, it has enough bandwidth, high sensitivity and also, due to the easiness in handling to detect the resultant magnetic field of the excitation coil [11].

This work aims to classify different aging states of a heat-resistant stainless steel tube using the ECT method and a machine learning algorithm. A pancake probe has been fabricated using a Hall sensor as

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https://doi.org/10.1016/j.measurement.2018.05.101
Received 27 September 2017; Received in revised form 23 May 2018; Accepted 25 May 2018

sensing element. As the reformer tubes are exposed to harsh and oxidizing environments, a ferromagnetic layer grows on the tube external surface, composed by an oxide scale and a chromium depleted zone [16–18]. The presence of this external surface, with higher magnetic permeability, affects the inspection by electromagnetic methods, the magnetic flux is "short-circuited" by this layer and does not penetrate to the inner material thickness. Therefore, it is necessary to saturate magnetically the external surface in order to suppress the unwanted magnetic field effect caused by this layer on the ECT results. Thus, an electromagnet was placed on the tube external surface to magnetically saturate the ferromagnetic layer. This saturation, decreases the magnetic permeability and approaches the non-ferromagnetic characteristics of the base metal. A finite element model (FEM) was developed in order to estimate the eddy currents penetration in the sample with and without the ferromagnetic external surface. In addition, the Support Vector Machine (SVM) method has been used to build a classifier model in order to predict the aging state of the samples. SVM is an useful method for classification and regression, permitting to recognize patterns and other learning tasks [19,20]. The developed methodology can be a reliable method to correlate changes in the extracted features from the ECT signal with the aging state of the material. The change in amplitude and phase-shift of the signals showed correlation with the sample aging, therefore can be classified in real time using the SVM model.

2. Experimental procedure

2.1. Test specimen

All samples were obtained from the same reformer tube that was in service during 90,000 h. The temperature along the tube length was heterogeneous causing significant microstructural variations. Three samples, with different aging states, were cut from different tube positions. The diameter, thickness and length of the three samples are: 110 mm × 12 mm × 100 mm. During aging, the as-cast steel undergoes several microstructural changes such as precipitation of secondary chromium carbides and the in-situ transformation of NbC into G-phase [21–23]. This process leads to mechanical properties changes and, consequently, to the electromagnetic properties variations [24]. Table 1 shows the service temperature and the aging state of the tested samples. The aging state criterion has been defined elsewhere [1], which classifies the aging in six different stages, from I to VI.

2.2. Experimental setup

Fig. 1 shows the block diagram of the eddy current system that was developed and used to obtain the experimental dataset. The system consists of a sinusoidal current generator, a probe, a power supply and a DAQ. The sinusoidal current generator is used to drive the eddy current probe. The probe consists of a cylindrical excitation coil and a Hall sensor, placed at the bottom axial center of the excitation coil in order to detect the magnetic field perpendicular to the surface of the test specimen. The output voltage from the Hall-sensor was amplified with an instrumentation amplifier with a gain factor of 101. The gain of this amplifier is set by connecting a single external resistor (R_G) between pins 1 and 8, calculated by Eq. (1) [25]. In this study, R_G was set in 0.5 kΩ.

Table 1
Characteristics of the analyzed samples.

Sample	Service temperature [°C]	Aging state
A	600	I
B	700	III
C	1000	VI

$$G = 1 + \frac{50\ \text{k}\Omega}{R_G} \tag{1}$$

A current sampling resistor of 10 Ω is connected in series with the coil. The voltage drop across this resistor was used to estimate the current and calculate the phase difference between the coil current and the Hall-sensor voltage. The probe was fed with a sinusoidal excitation current with 100 mA of amplitude at a frequency of 2 kHz. The excitation of the probe coil was set with constant current amplitude in order to avoid changes in the coil impedance [26]. As the external wall of the tube presents a ferromagnetic external surface [18,27], it is necessary to magnetically saturate this layer. For this purpose, it was used a partial saturation eddy current (PSEC) system that includes a U-shape electromagnet. The ECT probe is placed between the two poles of the electromagnet, as shown in Fig. 1. A DC power supply was used to drive the electromagnet up to 2 A of DC current, producing a maximum magnetic field of 22 kA/m. A data acquisition board (DAQ) was used to acquire the signals from the probe, it was employed a National Instruments (NI-6363) DAQ with 16 bit ADC resolution, timing resolution of 10 ns and timing accuracy of 500 ppm of sample rate. The data acquisition was made at a sampling rate of 1.2 MS/s. Matlab software was used to obtain the measurements and post-processing the data. The lift-off distance (air gap between the sample and probe) between the sample and probe is approximately 1 mm. The data acquisition was obtained by scanning 1000 evenly distributed points taken on the surface of the three samples.

The flowchart depicted in Fig. 2 corresponds to the procedure used to acquire the signals from the ECT probes. The probes are moved using an automated positioning system with two degrees of freedom. The amplitude and phase-shift of the probe signals are extracted using a sine-fitting algorithm; these parameters are used to train and test the SVM classification algorithm.

2.3. Signal processing

A three-parameter sine-fitting algorithm described in [26] was used to extract the parameters of the sinusoidal waveform. The amplitude (A) of the magnetic sensor voltage (magnetic field amplitude) and the phase shift (φ) between the excitation current and the magnetic sensor voltage were extracted from the expression (2) [28].

$$Y(t) = A_I\cos(2\pi ft) + A_Q\sin(2\pi ft) + C \tag{2}$$

where A_I is the in-phase amplitude, A_Q the in-quadrature amplitude, f the frequency and C the off-set. In this study, C was neglected. The amplitude A can be computed from the A_I and A_Q using the expression (3). The φ is also obtained from the same parameters A_I and A_Q using the Eq. (4).

$$A = \sqrt{A_I^2 + A_Q^2} \tag{3}$$

$$\varphi = arctan\left(-\frac{A_Q}{A_I}\right) \tag{4}$$

2.4. Computer simulation model

As described in [27], the samples with aging state I and VI exhibited homogeneous magnetic behavior along the thickness tube area. That study developed a model in order to quantify the magnetic susceptibility and the magnetization curves in samples with aging I and VI. Thus, in order to observe the external surface influence in the skin depth (δ), samples A and C were simulated in OPERA® 3D/ELEKTRA software using the relative permeability values obtained in [27]. The distribution of the eddy current density along the depth of conductive materials depends on the frequency of the current imposed on the excitation coil, the magnetic permeability and the electrical conductivity of the sample [6]. As described in Section 2.2, the probe frequency was