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Review Articles

Magnetic evaluation of the external surface in cast heat-resistant steel tubes with different aging states

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A B S T R A C T

Heat-resistant austenitic stainless steels have become the principal alloys for use in steam reformer tubes in the petrochemical industry due to its mechanical properties. These tubes are typically exposed to severe operational conditions leading to microstructural transformations such as the aging phenomenon. The combination of high temperatures and moderate stresses causes creep damages, being necessary to monitor its structural condition by non-destructive techniques. The tube external wall is also subjected to oxidizing atmospheres, favoring the formation of an external surface, composed by an oxide scale and a chromium depleted zone. This external surface is usually not taken into account in the tube evaluation, which can lead to erroneous estimations of the service life of these components. In order to observe the magnetic influence of this layer, two samples, exposed to different operational temperatures, were characterized by non-destructive eddy current testing (ECT), scanning DC-susceptometer and magnetic force microscopy (MFM). It was found that the external surface thickness influences directly in the magnetic response of the samples.

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1. Introduction

Centrifugally cast-heat resistant stainless steels are suitable for work in severe operational conditions while maintaining their high mechanical performance and creep resistance to temperatures up to 1000 °C [1]. Modified HP alloys have been increasingly used in petrochemical industry as radiant tubes in reformer and pyrolysis furnaces [2]. Steam reformer furnaces are used for large-scale production of hydrogen by catalytic reactions [3]. Hydrogen production furnaces tubes are assembled in columns, averaging in length from 10 m to 14 m, outer diameter from 100 mm to 200 mm and thickness between 10 mm and 20 mm [1]. Although their lifetime is projected to 100,000 h [3–5], the remaining life depends on several variables, such as internal pressure, wall temperature, time in service and structural strengths that can originate creep damages, crack growth and corrosion.

In normal operational conditions, the HP alloy exhibits microstructural changes according to temperatures, being this process known as aging. Besides the aging phenomenon, a complex oxide scale is usually formed on the tube external wall. The oxide scale composition and thickness is strongly dependent on the oxidizing environments and its kinetics variables [6,7]. Pyrolysis tubes, that present carburization damages in their internal walls, can also display an oxide scale in their external walls, because those walls are in contact with oxidizing environments. Some studies have detected that this oxide scale presents a ferromagnetic behavior [8–11] which could decrease or extinguish the signal obtained from the internal wall. The solution to this problem has been the use of an external DC-magnetizer in order to saturate this effect and promote the correct acquisition of the signal from the carburization effect in the internal wall.

It has not been possible, so far, to acquire significant signals related to the aging process of this material in presence of the external surface. In this case, it would be necessary to understand exactly how the presence of this layer affects the signal. The present study aims to assess the effect of the external surface on the magnetic response of the material using eddy current testing (ECT), scanning DC-susceptometer and magnetic force microscopy (MFM) techniques. There is, as of yet, no literature correlating the external surface formation with the magnetic response in samples coming from steam reformer tubes.

2. Experimental procedure

2.1. Samples

The chemical analysis was performed in an as-cast sample using a carbon and sulfur analyzer and the X-ray fluorescence and plasma atomic emission spectrometers. As shown in Table 1, the elements are within the tolerance stablished by the ASTM-A608 standard [12]. However, it is observed the presence of Nb and Ti, indicating that is a modified HP alloy. The addition of these elements improve the mechanical properties when the alloy is exposed to high temperatures [2,13,14].

The steam reformer tubes are subjected to different heating along their length, receiving an aging classification varying from I to VI [4]. This criterion has been adopted by other authors and also used in this work. Two HP-NbTi samples with state of aging III and VI were analyzed. The samples were taken from the same reformer tube, which was in service during 90,000 h. The eddy current inspection was performed on the tube external wall. On the other hand, the samples for DC-susceptometer and MFM measurements were extracted from the tube cross-section. Table 2 shows the characteristics of the samples.

2.2. Eddy current testing (ECT)

The eddy current inspection was performed using the OmniScan Olympus equipment. It was used an absolute probe, composed by a ferrite core in which 1000 turns of cooper wire were wound [15]. The probe frequency was set in 5 kHz, reaching a depth of penetration of approximately 6.65 mm in as-cast samples. Olympus equipment provides the results in the impedance plane. The eddy current signals were obtained by balancing the coil in air and then placing on the test material (liftoff). In order to classify the magnetic response of the samples, a standard block of calibration, with eight different materials, was used to differentiate ferromagnetic and non-ferromagnetic materials [16]. The calibration block was also used for setting up the equipment. The materials classified as ferromagnetic exhibited a signal with phase angle between 90° and 180°. In contrast, materials classified as non-ferromagnetic presented a phase angle between 180° and 270°.

The eddy current measurements were conducted along the tube external wall. These results were presented in two forms, through the contrast map and impedance plane. For the contrast map, the external tube surface was divided in regions evenly distributed along the perimeter and length, as shown in Fig. 1. Thus, the eddy current measurements were performed in each region acquiring the phase angle, which is calculated by the inverse tangent of the inductive reactance and resistance ratio.

After the data acquisition, the external surface was milled off to a depth of 1 mm in an area of approximately 50 mm × 50 mm, in order to evaluate the influence of the external surface on the magnetic response. After this procedure, the impedance plane signals were obtained with and without this external surface. The curves were obtained when the probe to sample distance (liftoff) is changed

2.3. Scanning DC–susceptometer

The basic principle of the scanning DC-susceptometer consists in applying a uniform DC magnetic field to the sample perpendicularly to the scanning plane, and measuring the induced or remanent magnetic response in the same direction. The susceptometer is equipped with a Hall axial gradiometer that virtually eliminates the applied field, thus the resulting output field (B_z) is the magnetic response from the sample [17]. It has a 200 μm spatial resolution and is able to detect magnetic moments down to 10^{-10} Am^2. Samples from the cross section of the tube, with dimension of ca. 13 mm × 10 mm × 1.8 mm, were exposed to a 400 mT magnetic field for a few seconds. The field is subsequently turned off and the remanent response was mapped at a 140 μm liftoff over a 10 mm × 15 mm area. Later on, a line drawn along the tube thickness (red dashed line), as shown in Fig. 2, is extracted from the complete map and visualized.

Table 1
Chemical composition of an as-cast austenitic HP-NbTi alloy (weigh%).

Cr	Ni	C	Mn	Si	P	S	Nb	Ti
25.5	35	0.54	1.3	1.6	0.02	0.006	1.13	0.083

Balance: %Fe.