Eddy current false indications in austenitic steel and titanium alloys 
heat exchanger tubes activated by stress

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Abstract

Eddy current non-destructive examination with the internal bobbin type probes is a mandatory test for heat exchanger tube manufacturing due to its high sensitivity to the different type discontinuities. In this paper, we want to highlight the problems related to the false indications in the nonmagnetic austenitic steel and titanium alloys due to magnetic inclusions. There are known origins for magnetic inclusions in stainless steel like chips or filings as a result of ferrous tool application, alloy depletion concerned with oxidation or corrosion, and magnetite deposits. The little-known origin of magnetic inclusions is concerned with stress induced martensitic transformation is shortly analyzed in this report as a possible mechanism for the creation of the magnetic inclusion in austenitic steel as in titanium alloy tubes. The phase transformation and as the result the presence of magnetic inclusions is generated by the activation of the spin magnetic moments of the free electrons under stress influence. These inclusions can radically influence the eddy current signal due to quite large difference in relative magnetic permeability but can be differentiated from real defects by re-inspection of the suspicious tubes at reduced operational frequency. During the eddy current examinations of stainless steel and titanium tubes by an internal probe, the false indications in tubes have been detected. The presence of these isolated indications is located always in the same length of the tested tube. The indications were detected in each tube and the signal amplitude was estimated in the range of 40-50% of the acceptance reference level. In stainless steels, the false indications generated are higher than in titanium alloys.

KEYWORDS: Eddy current; False indications; Magnetic inclusions; Austenitic steel; Titanium alloy; Stress induced

1. Introduction

Nondestructive testing (NDT) plays a crucial role in the safety and reliability of heat exchanger tubes (HET) and other responsible components used in the power generation
and chemical industry as an important tool possible to prevent critical failures and undesirable unplanned shutdowns. The eddy current (EC) NDT method has been routinely applied during the HET manufacturing and in-service life to detect dangerous defects of different types like cracks, corrosive pitting, or wall loss [1-4]. The selection of the HET material is a very important factor for long-term exploiting life along with the reliable NDT inspection [5]. In this publication, some factors needed to be considered for material selection are discussed including corrosion and erosion resistance, stress susceptibility to corrosion cracking, thermal and mechanical properties, temperature range, etc.

At present, the HETs are inspected mostly by the internal bobbin-type EC probe application. The main reasons for such choice are high inspection speed, lowest price, large flaw detection experience, and established tradition. At the same time, the internal rotational or array EC probes were developed with the goal to minimize some disadvantages of bobbin-type EC probe such as low sensitivity to circumferential cracks and unrecognizing or incorrect interpretation when several defects are situated with the same axial location [4].

During the EC inspection of a stainless steel and titanium HET, some anomalous (or false) indications which are not concerned with real discontinuity presence have been observed. These indications have real derivation related to the material’s phase heterogeneity, and the nature and the origin of which is the subject of the next analyses and investigations. In the present report, we focused on the possible origins related to false EC indications.

Difficult inspection situations and related anomalous indications which could be mistaken for real discontinuity (defect) detection were analyzed in advanced manual and publication concerned with EC test of HET by internal EC probes (e.g. [6, 7]). In these documents, it was mentioned that some anomalous indications were related to magnetic inclusions (like chips or filings) encountered in non-magnetic material as the result of steel tooling or handling equipment applied during tube manufacturing. In some cases, the non-magnetic stainless steel can become magnetic as a result of alloy depletion concerned with oxidation or corrosion. False indications also can be created by magnetite (Fe₃O₄) deposits characterized by magnetic non-conductive properties. The possible origin of magnetic inclusion (not included in the presented above documents) is concerned with creation of the martensitic phase in the alloys (like stainless steel) under the stress or strain (deformation) influence. This mechanism appropriated for many metastable austenitic stainless steel (and some titanium alloys) will be analyzed in the next section. All possible origins responsible for false indications generated by magnetic inclusions are summarized in the next Table 1.

| Table 1. Possible origins responsible for false indication generated by magnetic inclusions |
|-----------------|------------------------------------------------------------------------------------------|
| 1.  | Chips or filings as a result of ferrous steel tool application                              |
| 2.  | Alloy depletion concerned with oxidation or corrosion                                     |
| 3.  | Magnetite (Fe₃O₄) non-conductive deposits                                                 |
| 4.  | Stress or strain activated martensitic transformation                                      |

Magnetic inclusions in non-magnetic alloys can radically influence the EC signal due to quite large difference in relative magnetic permeability (\(\mu \approx 1.0\) for non-magnetic alloys and \(\mu \gg 1.0\) for magnetic inclusion).
To distinguish between signals created by magnetic inclusions or deposits and discontinuities (defects) special procedure was proposed [6, 7]. Following this procedure, magnetic inclusions can be differentiated from real defects by re-inspection of the suspicious HET at the reduced operational frequency as illustrated in figure 1.

![Fig. 1. Typical signals obtained from the defects situated on the inner (ID) or outer (OD) surfaces of inspected tube and magnetic inclusion (M) at the operational frequencies 250 kHz (a), 50 kHz (b), and 10 kHz (c).](image)

A magnetic inclusion creates the EC signal whose phase (angular) separation from the lift-off direction in the complex plane increases when the operational frequency is reduced and the signal response created by real discontinuity “is just the opposite” [6].

2 Martensitic transformations in austenitic steel and titanium alloys as the possible mechanism of magnetic inclusion creation

Let us discuss the possible mechanism for magnetic inclusion creation related to martensitic transformation not mentioned in the known standard manuals [6, 7].

Austenite is known also as gamma-phase iron (γ-Fe). Its primary crystalline structure is face-centered cubic when in a single unit of austenite, atoms are situated at each corner of the cube, with an atom of another element in the center of the cube's faces. This peculiarity prevents austenitic steels from being hardenable by heat treatment and makes them essentially non-magnetic. Pure austenitic steel is unstable and cannot exist at "room" temperature. To stabilize austenitic steel at “room” temperatures, austenite-stabilizing elements (e.g. nickel, manganese, and nitrogen) are added. The corrosion-resistant alloys of the Incoloy family are mostly chromium or nickel-based and belong to the category of super austenitic stainless steels.

Martensite is formed by the quenching (rapid cooling) of the austenite form of iron at a high rate of cooling so that carbon atoms do not can to diffuse out of the crystalline structure in large enough quantities to form cementite (Fe₃C). As a result of the quenching, the face-centered cubic austenite transforms into a highly strained body-centered tetragonal martensite form that is supersaturated with carbon. The application of external elastic stresses or deformations increases the amount of martensite formed and raises the temperature at which it begins to form. When austenite is deformed, two types of martensite occur: stress induced martensite initiated by stresses below the yield strength of austenite and deformation (or strain) martensite concerned with respectively higher temperatures [9,10].

Within the scope of the EC method, it is important to analyze the difference between austenite and martensite concerned with the magnetic properties [6]. The perfectly austenitic steels are non-magnetic (paramagnetic), while the perfectly martensitic (or ferritic) steels are ferromagnetic. The majority of structural austenitic stainless steels (AISI 304, 316, etc) are paramagnetic (μ ≈ 1.0) due to an austenitic microstructure.
the same time, austenitic steels can have transformed into a ferromagnetic state when some martensite phase is produced by cold work deformation, hydrogen charging, or ion irradiation [7-10]. So, austenitic steels with some quantity of martensite fraction or inclusions reveal the magnetic behavior. This factor creates the fundamentals for the application of EC and magnetic methods for the evaluation of the structural state of austenitic steels [11-14].

It is not widely known that similar martensitic transformations are observed in some titanium alloys when the magnetic martensitic phase are created in primary nonmagnetic materials [15-17]. In the last study, the stress-induced martensitic transformation in a metastable β titanium alloy (Ti–10 V–2Fe–3Al) during compressive deformation was investigated [17].

3 False indications obtained during the austenitic steel and titanium alloys heat exchanger tube inspection

During the EC examinations of stainless steel and titanium tubes by internal EC probe, the false indications in tubes have been detected. These isolated indications are located always in the same length of the tested HET.

The next figures present the false indications obtained during the EC inspection of HET due to magnetic inclusions influence (Figures 2-3). Inspections were carried out by ECTAINE from EddyFi Technologies with a bobbin type internal EC probe at the operational frequency of 400 kHz.

![Figure 2. False indication in the HET created by magnetic inclusion](image1)

![Figure 3. False indication in the HET created by magnetic inclusion](image2)
Unfortunately, at present there is no way to repeat the results of testing at lower frequencies as proposed in Canadian standard [6,7]. Such testing is planned during the next phase of similar inspections. As a possible alternative, the possibilities of harmonic analysis of the received EC signals will also be analyzed and investigated in order to separate the signals associated with magnetic inclusions.

3. Conclusions

The problems related to the false indications in the nonmagnetic austenitic steel and titanium alloys due to magnetic inclusions was highlighted. These inclusions can radically influence the eddy current signal due to quite large difference in relative magnetic permeability but can be differentiated from real defects by re-inspection of the suspicious tubes at reduced operational frequency. The origins for magnetic inclusions in stainless steel like chips or filings, alloy depletion concerned with oxidation or corrosion, and magnetite deposits are indicated. The magnetic inclusions concerned with stress induced transformation is analyzed as a possible mechanism for the creation of the magnetic inclusions. This transformation and the presence of magnetic inclusions is generated by the activation of the spin magnetic moments of the free electrons under stress influence. During the eddy current examinations of stainless steel and titanium tubes by an internal probe, the false indications in tubes have been detected.

References


