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# EVALUATION OF FERROMAGNETIC HEAT EXCHANGER TUBES BY EDDY CURRENT TESTING METHOD

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***Abstract:*** *Ferromagnetic tubes are used in most of heat exchangers installed in industrial areas, such as chemical and petrochemical industries. To assure its normal operation these tubes should be evaluated periodically, in order to detect and evaluate discontinuities that can promote the equipment failure. For tubes manufactured from ferromagnetic materials, conventional eddy current inspection techniques are not capable to detect and evaluate discontinuities present in wall tube, due the influence of the variable magnetic permeability of the material during the inspection. This paper presents a study concerning the use of eddy current testing with a DC magnetization technique for ferromagnetic tubes inspection. Samples of ASTM A 179 carbon steel tubes having artificial discontinuities were studied. The results obtained show that for some particular size and position of the discontinuities this technique can be employed. The main advantages and restrictions to the application of this technique are also discussed.*

***Keywords:*** *eddy current, nondestructive examination, ferromagnetic materials, DC magnetization*

## 1. INTRODUCTION

Heat exchangers are widely used in many industrial areas such as chemical, petrochemical and nuclear industries. Depending on its characteristics and applications they can contain from few tens up to thousands of tubes. During its operational life, tubes of heat exchangers can be submitted to harmful conditions, such as the service temperature, pressure of operation and environment, that can promote the failure of the equipment. Consequently, they should be periodically inspected, in order to assure the heat exchanger integrity and avoid the occurrence of accidents and unnecessary outage.

The inspections of heat exchangers tubes manufactured from non-ferromagnetic materials, such as stainless steel, titanium, aluminum alloys, cooper alloys, etc., the post-manufacturing inspections as well as the in-service inspections are performed using conventional techniques of eddy current testing, presenting a high sensitivity and reliability. Information referent to discontinuity depth and position can be obtained making possible a more accurate evaluation of the tubes integrity. However, for ferromagnetic materials, the inspection using eddy current testing presents strong restrictions, due to the magnetic characteristics of those materials.

The changes occurring in the magnetic permeability of the material during the test promote a decrease in the test sensitivity for small discontinuities detection. In this situation, special test techniques should be used, such as remote field technique and DC magnetization technique.

## 2. PRINCIPLES OF EDDY CURRENT TESTING USING DC MAGNETIZATION

Eddy current testing is based upon the induction of electric currents on conductive materials and monitoring its behavior. It is sensitive to changes in electrical conductivity (σ), magnetic permeability (μ) and the geometric characteristics of the of the tested material, such us the presence of structural discontinuities (ASNT, 1986). Its application for non-ferromagnetic tubes inspection have been demonstrated for tube materials such as zircaloy-4 (Silva Jr. & Alencar, 1996) and titanium (Silva Jr. & Alencar, 2000). Titanium tubes are used in steam condensers in nuclear power plants. An internal probe is introduced into each tube and the inspection is performed according to ASTM or ASME Standards (ASME, 1998). For ferromagnetic materials examination, it is necessary to superimpose a DC magnetic field on AC eddy current signal, in order to reduce the effect of the magnetic permeability changes and increase the test sensitivity. For non-installed tubes an adequate DC magnetic field can be produced using an external magnetization coil, with enough power to promote the magnetic saturation of the material. In this situation its behavior is similar to a non-ferromagnetic material. However, for installed tubes, the use of an external magnetization coil is not possible. Internal magnetization coils, assembled in the test probe are used. The main limitation in this case is the low value of the magnetic field generated, as a function of the small size of the magnetization coil and the low values of electrical current that can be applied to it (Cecco & Van Drunen & Sharp, 1983). To overcome this limitation, eddy current probes used for this purpose are manufactured using a ferromagnetic core with high magnetic permeability. This material increases the magnetic field generated by the internal magnetization coil, increasing the test sensitivity. Materials commonly used are Permendur alloy and FeCoNb alloy (Soares et al, 1992) allowing the examination of many ferromagnetic materials in better conditions when compared with the conventional techniques.

## 3. EXPERIMENTAL METHODOLOGY

### 3.1. Materials

In this study tubes of ASTM A 179 carbon steel were used. A total of eight tubes, presenting different artificial discontinuities and wall thickness were prepared and separated in three distinct sets, as shown in Tab. (1), Tab. (2) and Tab. (3).

Table 1. Set 1: samples with different wall thickness and through wall holes diameter

| Test Specimen | Tube Wall Thickness (mm) | Through Wall Hole Diameter (mm) | | | | |
|---|---|---|---|---|---|---|
| 1 | 2.28 | 0.50 | 1.00 | 2.00 | 4.00 | 5.00 |
| 2 | 2.00 | | | | | |
| 3 | 1.00 | | | | | |

Table 2. Set 2: Samples with different wall thickness and external flat bottom holes depth.

| Test Specimen | Tube Wall Thickness (mm) | External Flat Bottom Holes with 4 mm Diameter | | | | |
|---|---|---|---|---|---|---|
| | | Hole Depth (% of wall thickness) | | | | |
| 4 | 2.28 | 100% | 80% | 60% | 40% | 20% |
| 5 | 2.00 | | | | | |
| 6 | 1.00 | | | | | |

Table 3. Set 3: Samples with different wall thickness and internal flat bottom holes depth

| Test Specimen | Tube Wall Thickness (mm) | Internal Flat Bottom Holes with 4 mm Diameter | | | | |
|---|---|---|---|---|---|---|
| | | Hole Depth (% of wall thickness) | | | | |
| 7 | 2,28 | 100% | - | 60% | 40% | 20% |
| 8 | 2,00 | 100% | 80% | 60% | 40% | 20% |

The artificial discontinuities were machined in the tube wall samples using an electrical discharge machine.

### 3.2. Instrumentation

Experiments were performed using an ECT – MAD8D eddy current testing equipment with four frequency channels and a data acquisition and analysis software. Signals referent to the tube wall discontinuities were acquired using a special internal eddy current probe with a high permeability ferromagnetic core, a DC magnetization coil and a DC current source. The electrical current applied to the DC magnetization coil was enough to promote a partially magnetization of the sample in the test region but not to magnetically saturate the material.

### 3.3. Data Acquisition and Test Results

Three different test frequencies, in the range of medium, low and high frequencies values were used, in the channels 1, 2 and 3 respectively. Only the signals with the signal to noise ratio above 3 are presented. The experiment was carried out in three steps. In the first step the signals referent to the discontinuities present in the test specimens 1, 2 and 3 (through wall holes with different diameters) were acquired in order to find the minimum diameter hole detectable by the three test frequencies used. The results obtained are shown in Tab. (4).

Table 4. Results referent to set 1: test specimens with different wall thickness and through-wall hole diameter

| Through Wall Hole Diameter (mm) | Signals Amplitude (V) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Test Specimen 1 | | | Test Specimen 2 | | | Test Specimen 3 | | |
| | Test Frequency | | | Test Frequency | | | Test Frequency | | |
| | Medium | Low | High | Medium | Low | High | Medium | Low | High |
| 4.8 | - | 3.88 | 3.28 | 6.08 | > 6.5 | 4.16 | 11.8 | 12.39 | 4.79 |
| 4.0 | - | 2.66 | 2.13 | - | - | 2.06 | 13.01 | 10.49 | 5.12 |
| 2.0 | - | - | - | - | - | 1.35 | 11.4 | 7.18 | 3.39 |
| 1.0 | - | - | - | - | - | - | - | - | 2.44 |
| 0.5 | - | - | - | - | - | - | - | - | - |

From the examination of the results obtained in this step, the smaller discontinuity (through wall hole) detected was the 4 mm diameter hole. For this reason, it was chosen as the artificial discontinuity to be machined in the test specimens 4 to 8.

In the second step, the signals referent to the external discontinuities present in the test specimens 4 to 6 were acquired. These discontinuities consist of flat bottom holes of 4 mm diameter with depths corresponding to 100%, 80%, 60%, 40% and 20% of the tube wall thickness. The goal in this step was to determine the minimum depth of the 4 mm diameter external flat bottom hole that can be detected by the test system. The results obtained are shown in Tab. (5).

Table 5. Results referent to set 2: test specimens with different wall thickness and external flat bottom holes with different depths

| Flat Bottom Hole Depth (%) | Signals Amplitude (Volts) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Test Specimen 4 | | | Test Specimen 5 | | | Test Specimen 6 | | |
| | Test Frequency | | | Test Frequency | | | Test Frequency | | |
| | Medium | Low | High | Medium | Low | High | Medium | Low | High |
| 100 | 3.38 | 4.41 | 4.60 | 4.44 | 6.31 | 4.00 | 8.00 | 13.14 | 4.41 |
| 80 | - | - | - | 7.37 | 5.25 | - | 15.91 | 14.00 | 7.95 |
| 60 | - | - | - | 5.81 | 3.73 | - | 11.49 | 11.79 | 5.50 |
| 40 | - | - | - | - | - | - | 8.13 | 8.19 | 3.97 |
| 20 | - | - | - | - | - | - | - | - | 2.16 |

In the third step, the signals referent to the internal discontinuities present in the test specimens 7 and 8 were acquired. These discontinuities consist of flat bottom holes of 4 mm diameter with depths corresponding to 100%, 80%, 60%, 40% and 20% of the tube wall thickness. The goal in this step was to determine the minimum depth of the 4 mm diameter internal flat bottom hole that can be detected by the test system. The results obtained are shown in Tab. (6).

Table 6. Results referent to set 3: test specimens with different wall thickness and internal flat bottom holes with different depths

| Flat Bottom Hole Depth (%) | Signals Amplitude (Volts) | | | | | |
|---|---|---|---|---|---|---|
| | Test Specimen 7 | | | Test Specimen 8 | | |
| | Test Frequency | | | Test Frequency | | |
| | Medium | Low | High | Medium | Low | High |
| 100 | - | - | 3.91 | - | - | 3.72 |
| 80 | - | - | - | 5.23 | - | 3.60 |
| 60 | - | - | 3.33 | - | - | 2.39 |
| 40 | - | - | 1.81 | - | - | 2.20 |
| 20 | - | - | - | - | - | 1.65 |

## 4. RESULTS DISCUSSION

With the test conditions adopted to perform the experiments, the 4 mm diameter through wall hole was the smaller discontinuity detected by the test system for all test specimens of different wall thickness (test specimens 1, 2 and 3).

Another point that can be observed is related with the test sensitivity. It increases as the tube wall thickness decreases. This effect is due to the increase of the magnetization level in the test region generated by the magnetization coil of the eddy current probe. For the tubes with a wall thickness of 1.0 mm it was possible to detect a 1.0 diameter through-wall hole (set 1, test specimen 3). The same behavior was observed relating to the test sensitivity for detection of the external and internal flat bottom in the sets 2 and 3 presented in Tab. (5) and Tab. (6).

From the results obtained for the test samples 5 and 8 (wall thickness of 2.00 mm) it can be seen that the use of different test frequencies can be advantageous. With the use of a high test frequency, the sensitivity to detect internal discontinuities has increased. In the same way, with the use of a low frequency, the sensitivity to detect external discontinuities has increased.

In some situations, the signal amplitude presented by a specific discontinuity was higher than the expected, as can be observed by the examination of Tab. (4) (test specimen 3) and Tab. (5) (test specimens 5 and 6). As the magnetization level generated by the magnetization coil is not enough to promote the magnetic saturation of the tube material in the test region, this effect can occur due to a local change in the magnetic material permeability.

## 5. CONCLUSIONS

The eddy current DC magnetization technique allows the detection of small discontinuities such as a 4 mm diameter flat bottom holes with depths of 20% of the wall thickness (for tubes with 1.00 mm of wall thickness) and 40% of the wall thickness (for tubes with 2.00 mm of wall thickness) in the conditions used in this study), thus, before its failure. The test sensitivity increases with the use of different test frequencies, allowing the detection of internal and external discontinuities in the tube wall. This fact recommends the use of test frequencies in different ranges (low, medium and high) for the inspection of tubes of ferromagnetic materials. The more adequate values for the test frequencies should be experimentally determined.

## 7. REFERENCES

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## 8. AUTHORIAL RIGHTS

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