EDDY CURRENT NDT: A SUITABLE TOOL TO MEASURE OXIDE LAYER THICKNESS IN PWR FUEL RODS

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ABSTRACT

Eddy current is a nondestructive test (NDT) widely used in industry to support integrity analysis of components and equipment. In the nuclear area it is frequently applied to inspect tubes installed in tube exchangers, such as steam generators and condensers in PWR plants, as well as turbine blades. Adequately assisted by means of robotic devices, that inspection method has been pointed as a suitable tool to perform accurate oxide layer thickness measurements in PWR fuel rods. This paper shows some theoretical aspects and physical operating principles of the inspection method, as well as test probes construction details, and the calibration reference standards fabrication processes. Furthermore, some data, experimentally obtained at INB laboratories and other technical information obtained from TECNATOM S.A. are presented, showing the accuracy and efficacy of such NDT method.

1. INTRODUCTION

Eddy current is a nondestructive test (NDT) widely used in industry to support integrity analysis of components and equipment [1]. In the aerospace industry, such test is widely used to measure aluminum foil and plates thicknesses and to detect surface and sub-surface cracks in structural components and in turbine blades. In the nuclear area it is frequently applied to inspect tubes installed in tube exchangers, such as steam generators and condensers in PWR plants [2], as well as steam turbine blades. Additionally, nuclear fuel cladding thicknesses have been measured after their manufacture and during their operational life by means of
eddy current test [3]. This paper describes a study about the use of eddy current test method as a nondestructive tool for nuclear fuel rods oxide layer thickness measurement in fuel rods installed in PWR plants. So, some theoretical aspects and physical operating principles of the inspection method, as well as test probes construction details, and the calibration reference standards fabrication processes, focused on oxide thicknesses measurement using that NDT are developed in the present paper. At last, some commercial inspections systems, capable to perform remote in-situ inspections of installed fuels, as well as typical registered data are shown.

2. EDDY CURRENT FUNDAMENTALS

Eddy current is a nondestructive test (NDT) based on the measurement of the behavior of induced eddy or parasite electrical current under or on the surface of conductive materials. Fig. 1 shows a typical arrangement employed to generate eddy current on a hypothetical conductor. Probe coil is fed with alternating current at a given frequency. As the coil is placed close to surface, a primary magnetic field induces eddy currents that flow through the material.

Penetration of eddy currents in the material is function of its electrical (resistivity) and magnetic (permeability) properties, as well as the operating frequency. For the applications concerning to flaw detection, the phase shift and exponential current intensity decreasing are the most important phenomena observed. For the objectives of this paper, the very important characteristic is the lift-off effect. In a simple way, a typical lift-off curve establishes characteristic complex impedance values for various probe-to-surface distances.

Fig. 2 shows a typical lift-off curve obtained for a given material. Initially, probe tip is positioned far away from the surface of the material (Air). So, it is placed closer to the surface, until reach the point B. So, significant changes can be verified in both, imaginary (X_L) and the real (R) components of the probe coil complex impedance (Z). Shape of such curve varies with material physical and electrical properties and the operating frequency.
Since oxide layers usually present very high electrical resistivity in comparison with the corresponding value found for the base metal, a lift-off effect based curve can be constructed, with the help of oxide layers thickness standards. In this case, for a given thickness, a unique value of $X_L$ can be registered. Using a reasonable number of standards an evaluation curve may be fitted and employed on real oxide layer thicknesses measurements.

![Figure 2: Typical lift-off curve](image)

**Figure 2. Typical lift-off curve**

### 3. REFERENCE CALIBRATION STANDARDS CONSTRUCTION

Fig. 3 presents a schematic diagram of a typical reference calibration standard useful for oxide layer thickness measurements of PWR fuel rods. Basically, oxide layers films of different thicknesses are deposited, at laboratory, on the external surface of tubes which composition and geometry are the same of the tubes to be inspected.

![Figure 3: Typical reference calibration standard schematic diagram](image)

**Figure 3. Typical reference calibration standard schematic diagram.**

For Zircaloy 4, film growing processes may be obtained in autoclaves, under a temperature of $350^\circ$C, in a 2000 ppm LiOH medium [4]. The oxidation process is time dependent and can reach by 30 to 40 days to achieve the maximum necessary thickness. Fig. 4(a) presents the aspect of some Zircaloy 4 tubes, attached to a mounting rack, as they were pulled out of the autoclave. In Fig. 4(b) the micrographic aspect of such oxide film (viewed in dark gray) in
that process can be observed. The graphic presented in Fig. 5 shows a correlation between process time and oxide film thicknesses.

Figure 4. Tubes removed from the autoclave (a). Micrographic aspect of oxide film (b).

Figure 5. Typical time versus oxide film thickness obtained curve.

4. **INSPECTION PROBES, EQUIPMENT AND SYSTEMS**

For the application of eddy current test, an inspection system, such as the ECT MAD8D [5] or other similar, and a couple of customized probes, operating at an optimum frequency of 650 kHz (specifically for Zircaloy 4) were employed. Geometry of the probes must match the curvature and diameter of the inspected tubes. Fig.6 presents the schematic diagram (a) and
actual aspect of the inspection probes (b). Notice the tube placed in one of the probes (reference) and the other (active). Probe type is absolute but their connection to the test system is differential. So measurements are always comparative.

![Schematic Diagram and Actual Aspect of Inspection Probes](image)

**Figure 6. Schematic diagram (a) and actual aspect of the inspection probes (b).**

Fig. 7 shows a typical evaluation curve that associates film thicknesses with voltages measured by the inspection system. With adequately adjusted operating parameters and well developed probes, reasonable linear response can be achieved.

![Evaluation Curve](image)

**Figure 7. A typical evaluation curve.**

When final destination of this NDT is its application to measure oxide layers thicknesses in externally located fuel rods, directly in the pool of PWR plants, the use of robotic scanning
systems, associated with a computer assisted three-dimensional positioning control and data acquisition system is mandatory. Fig. 8 shows the aspect of the robotic device used by SICOM-COR [6], a system that can be used for this purpose.

Figure 8. The robotic device of SICOM-COR system installed in a pool.

Fig. 9 presents a screenshot taken from another test system, named TEFRIS [7], indicated for individual irradiated rods inspection. Both systems were developed by TECNATOM S.A.

Figure 9. Screenshot taken from TEFRIS test system.
5. CONCLUSIONS

Eddy current has demonstrated to be a very suitable NDT tool to measure oxide layer thickness in PWR fuel rods. Using adequate equipment and test probes, good calibration reference standards and proper operating parameters, it can be said that the overall reliability of the method is excellent. For in-situ applications, the use of robotic systems, and computer assisted positioning and data acquisition system is mandatory and, due to access limitations the inspection is restricted to external fuel rods.

ACKNOWLEDGMENTS

The authors thank to TECNATOM S.A. for the cession of materials and technical information and to INB S.A., that allowed the access to experimental data and photographs. This work was supported by FAPEMIG - Fundação de Amparo a Pesquisa do Estado de Minas Gerais.

REFERENCES