

Eddy Current Inspection of WWER Steam Generator Tubes - Sensitivity of Bobbin Probe Technique

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Abstract. Eddy current inspections are being commonly performed as a routine part of nuclear power plant in-service inspections. Important questions during analysing of inspection results are sensitivity and reliability of applied eddy current technique. One can meet with following type of questions: Does inspection of all tubes in tube bundle mean detection of all defects? What is the sensitivity of applied technique? What is the probability of detection of damage with given depth? These questions of course deserve the answers, even if we know, that a simple question in many cases requires difficult answer.

The aim of this paper is to enlighten aspect of sensitivity of WWER steam generator heat exchanging tubes testing. Results of experimental works performed in VUJE, a.s. laboratories are presented. Scope of research work included eddy current measurements of the tubes encompassing stress corrosion cracking type of defects. Eddy current results have been compared to metallographic analysis results afterwards.

1 Introduction

Eddy current testing method is the main method for steam generator tubes inspection on the present. The main objective of inspection is to detect the target form of degradation of all, or at least of most of the damaged tubes. Undetected damaged tubes could cause a leakage before the next inspection. After damaged tube identification it is possible to make corrective action - plugging of a tube. Inspection programs and intervals are defined in nuclear power plant inspection directions. Inspections are being normally performed with period of four or eventually six years.

Important question from the point of view of evaluation of the tube bundle condition are both sensitivity and reliability of applied inspection technique. One can meet with following type of questions: Does inspection of all tubes in steam generator tube bundle mean detection of all defects? What is the sensitivity of the technique? What is the probability of detection of damage with given depth? The questions of course deserve the answers, even if we know, that a simple question in many cases requires difficult answer.

The PISC III Action 5 on steam generator tube inspection project has shown some results from the experimental evaluation of the performance of examination procedures and techniques available for Inconel 600 steam generator tubes 0.

Up to now, there is little information presented publicly concerning inspection of WWER steam generator tubes.

The aim of this paper is to enlighten aspect of sensitivity of eddy current testing of WWER steam generator heat exchanging tubes.

Therefore the results of experimental study started in 2001 the will be presented. Scope of the work included eddy current measurements of the tubes encompassing stress corrosion cracking type of defects. Technology development and manufacturing of this degradation type was realized at Nuclear Research Institute (NRI), Prague. Eddy current technique used included common eddy current instruments (MIZ 30, MIZ 27, Tecrad TC 5700) and standard middle frequency bobbin probes. Eddy current results have been compared to metallographic analysis results afterwards.

Data analysts were not influenced by prior knowledge of presence and parameters of defects during the inspections. Inspection results became known only after destructive analysis of the tubes.

2 Sensitivity of the method

Principle of the method is based on monitoring the probe coil impedance changes. Even though these impedance changes are relatively small (10^{-6}), they are detected using modern electronic instruments.

Method sensitivity is given first of all by its physical principle. It is possible to detect only the flaws sufficiently interrupting eddy currents flow. WWER steam generator tubes testing sensitivity is substantially influenced by a fact, that all relevant types of degradation are located on outside of the tube, while eddy current probe is moving inside the tube. In the direction from inner tube wall there is exponential decrease of eddy current flow density.

Furthermore, it is necessary to relate sensitivity to certain type of degradation. The reason is that flux of eddy current varies for different flaw geometries. Relations between signal amplitude and flaw dimension can express sensitivity of the applied eddy current technique for given degradation type.

3 Degradation of WWER steam generator tubes

Significance differences can be observed in degradation of tubes at various nuclear power plants, units and even within the same unit. At nuclear power plants, where the standards of water chemistry and regular washing are kept the tube damage presence is at minimum.

The main degradation mechanisms of WWER steam generator tubes are stress corrosion cracking (SCC) and pitting. All degradation forms are located on the outside of the tube.

3.1 Stress corrosion cracking

It is the most dangerous degradation mechanism. Initiation and propagation of this mechanism requires specific aggressive environment and stress acting. SCC cracks are specific by preferred orientation. Cracks propagate mostly perpendicular to the course of effecting tensile stresses. The crack orientation is in most cases axial (parallel to tube axis). A few circumferential cracks were observed.

This degradation form is located mostly under support plates. Location in free span is not so frequent.

3.2 *Pitting corrosion*

Pitting corrosion increases probability of SCC initiation. Higher volume of degraded (missing) material. Observed diameter: 0,1 to 5 mm. Maximum depth observed: 0,4 mm (28% tube wall). The depth of degradation is in general is not so high in comparison to SCC.

3.3 *Fretting*

Fretting is result of mechanical friction between support plate and the tube. Friction causes erosion of passive layer on tube surface and thereby contributes to corrosion attack. This degradation type was found only in negligible extend.

3.4 *Surface corrosion*

Surface corrosion is practically negligible providing the good chemistry regime.

4 Results of experimental study

4.1 *Experimental material*

As it was showed above the most dangerous form of degradation is stress corrosion cracking. As part of the assessment of in-service inspection of steam generator (SG) tubes three hundreds of SG tubes were used. Because cracked tubing from operating or retired steam generators is difficult and expensive to obtain and also the availability of such tubing is limited, it was necessary to produce „realistic“ cracks in tubes.

Realistic cracks in original austenitic SG tubes were prepared under laboratory conditions by Nuclear Research Institute Prague, Czech Republic. Tubes outer diameter is 16 mm. Wall thickness is 1,5 mm. Length of tubes varied from 160 to 300 mm. Material was austenitic stainless steel 08CH18N10T (AISI 321). In the most of test tubes realistic cracks were prepared in a corrosion environment under stress (SCC cracks). This method is based on tube exposure to the melted $MgCl_2 \cdot 6H_2O$ under mechanical pressure. Realistic crack depth profile was approximately elliptical. Metallographic cuts of realistic SCC crack in one of tested tube are in Picture 1. In a few test tubes EDM (Electro Discharge Machining) notches were manufactured. Total amount of tubes being used for results comparison between eddy current and destructive analysis was 61. This represents important amount also from statistical point of view also.

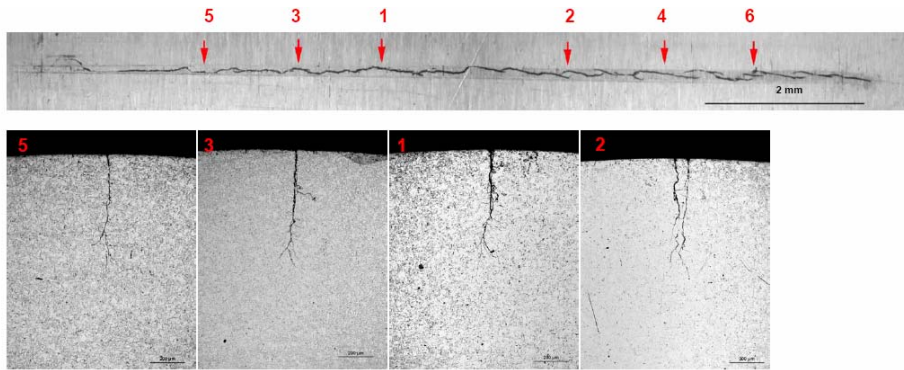


Fig. 1 Metallographic analysis of selected crack

4.2 *Standard bobbin probe results*

Sensitivity of technique was analyzed by comparison between the eddy current inspection results and the real dimensions (depth) of defects determined by means of destructive testing.

Tubes were inspected preferably using eddy current system MIZ 30-A and standard middle frequency bobbin coil probe with fill factor 0,78. Thereupon all tubes were analyzed using Eddyner software for data analysis.

Approximately 30% of total amount of the tubes have been measured and analysed by another two independent inspection teams as a part of round robin trials. Bobbin probes from three different producers have been used having fill factor from 0,74 to 0,78.

Standard in-service inspections procedures for data acquiring and data analysis were applied. Procedures are based on requirements of Slovak Electricity Company standard No. PN 01 5060. The standard determines testing frequencies and calibration standard. The main calibration flaw consists of 3 holes in one plain, circumferentially spaced by 120 degrees with depth of 100% of tube wall, diameter ϕ 1,3. The signal is calibrated to amplitude 10 V and to phase 40° for all used frequencies.

Experimental results showing relation between signal amplitude and crack depth are shown on the next picture. Signal amplitude of 0,3 - 0,5 V practically represents the material noise level.

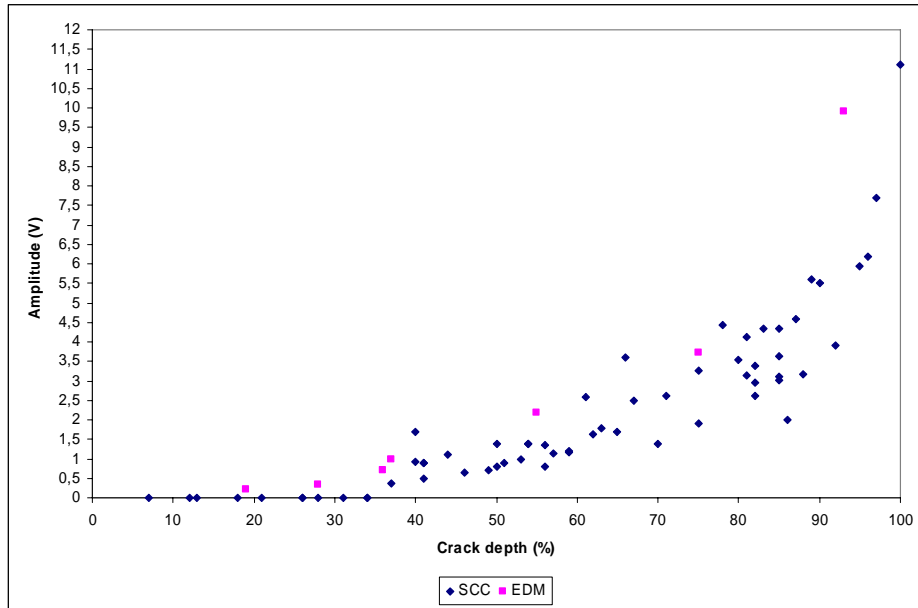


Fig. 2 Relation between signal amplitude and crack depth, frequency 100 kHz

For determination of crack length influence to signal amplitude, measurements on EDM notches were performed. EDM length was from 5 to 18 mm. EDM depth was from 54 to 57 % of tube wall. Results are shown on next graph.

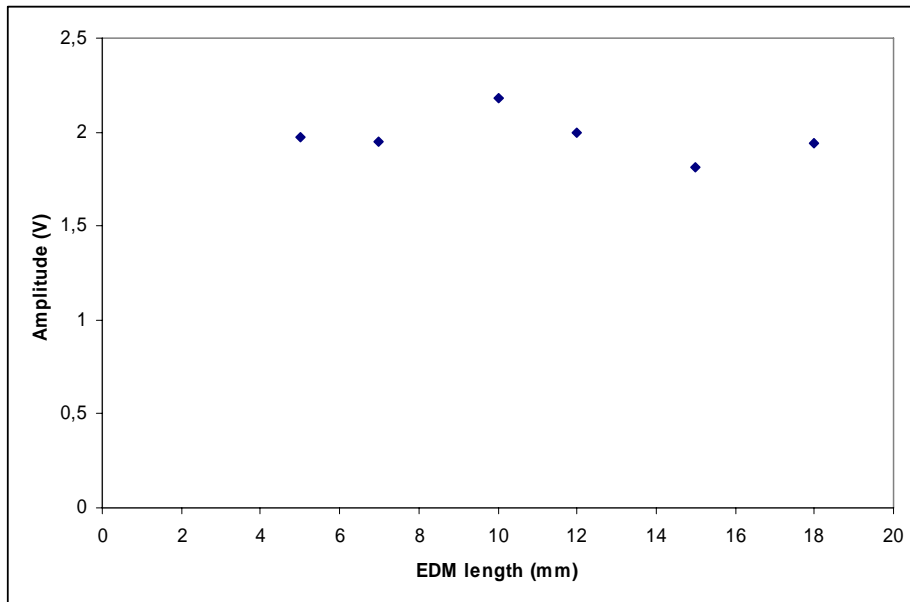


Fig. 3 Influence of EDM length on signal amplitude, frequency 100 kHz

As it can be seen from figure 2 procedures demonstrated good detection capability of SCC type of flaws. The detection of axial flaws deeper than 40% of the wall thickness was often good. This capability of detection fell markedly for external flaws with a depth less than 40% of the wall thickness. In general detection was not effective at cracks having defect shallower than 37%.

Based on experimental results, it can be said, that 37 % of tube wall represents break point from the point of view of SCC damage detection.

4.3 Probe design changes

As general guidelines for tube inspection, coil length and depth should be approximately equal to tube wall thickness. Some coil design rules are applicable to improve sensitivity to near surface defects. Unfortunately this will result in a decrease in sensitivity to external defects.

Taking into account all coil parameters contributing furthest to the probe sensitivity to external defects, following design changes were performed:

1. Increasing of the probe diameter (up to 12,3 mm - possible to use only in laboratory conditions).
2. Increasing of the width of the coil winding (to 2,0 mm).

Results of experimental measurement using the probe with maximum fill factor and coil width compared to the standard probe are shown in next picture.

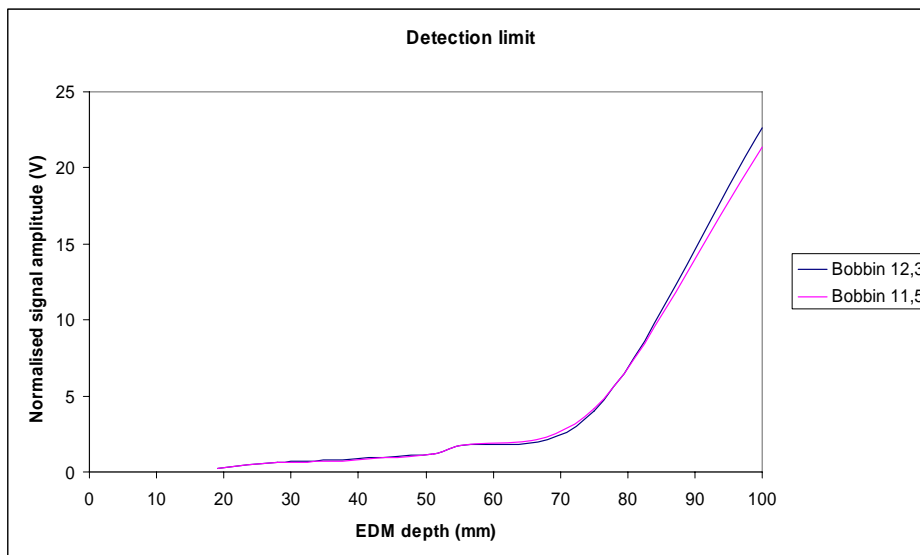


Fig. 4 Probe design changes results

Changes of coil parameters have not markedly improved probe neither the sensitivity of the inspection, nor the signal to noise ratio.

4.4 Application of signal processing (mixing)

Application of signal mixing gently contributed to increasing of sensitivity. It is necessary to take into mind, that amplitude of crack with depth between 30 and 40 % of tube wall are under the level of tube background noise. Without confirmation of indications on raw channels, there is an increase of false calls probability.

5 Conclusions

In general it can be said that 37 % of tube wall represents break point from the point of view of stress corrosion cracking damage detection. Since the SCC damage is the most dangerous degradation form, it is possible to consider this value as a detection limit in WWER heat exchanging tube testing using the eddy current method.

Sensitivity to SCC type of defects with a depth less than 40% of the wall thickness is low. In general detection was not effective at cracks having defect shallower than 37%.

Achieved results from inspection of WWER steam generator heat exchanging tubes are similar to results obtained from Inconel 600 tube material inspection, as it was presented in conclusions from PISC III, Action 5 on steam generator tube inspection 0.

Changes of coil parameters have not markedly improved probe neither the sensitivity of the inspection, nor the signal to noise ratio.

The objective of this work was not in the evaluation of the performance of examination procedures and techniques from the point of view of probability of detection, since experimental tubes length (from 150 to 300 mm) and total number of tubes (61) have not provided adequate conditions for simulating real inspection.

6 References

- [1] Bieth, M. at all: Final results of the PISC III round robin test on steam generator tube inspection, First International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, 20 - 22 October 1998, Amsterdam, Netherlands