Perspectives of EMAT Thickness Gauging: Operational Procedures, Benchmarking and Standardization Issues

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Abstract. A test program was carried to assess the performance of "no contact" EMAT probes in thickness evaluation of aged waterwall, super-heater and re-heater tubes. While PZT probes require a point is ground flat before testing, EMAT probes tolerate scale and thick oxide grown due to high temperatures. In addition the aged oxided surface improves the EMAT sensitivity allowing higher echoes and easier thickness evaluation. Procedures to evaluate residual wall thickness were assessed in lab tests. Measures were taken on aged tube samples with nominal thickness 3.5-5 mm. EMAT data were found quite in agreement (±0.2 mm) to destructive data. More measures were taken on calibration specimen machined from oxidised tubes to test and compare different wall conditions.

The results suggest the industrial exploitation of EMAT thickness testing shall benefit from a deeper understanding on the EMAT probe interaction with clean and oxidised tubes, standardized procedures, and from more efficient pulse/receive units. Conventional UT instruments and EMAT probes can test aged tubes with oxide and scale, but are ineffective on new clean surfaces. Portable flexible test units shall thus be designed to work on both new and aged tubes. Such steps would support the exploitation of EMATs for in-service thickness testing of boiler tubes without oxide removal. It is envisaged that manual and even automated thickness test procedure could be eventually set, based on present UT thickness gauging methods, possibly updating the current UT thickness gauging standard or issuing a dedicated one.

Introduction

Better in-service thickness gauging on waterwall super-heater and re-heater tubes can improve the evaluation of a boiler integrity and its expected residual life. Developments in the EMAT technology, proposed by EPRI, Babcock [1], Panametrics [2], indicate EMATs are well suited for testing aged boiler tubes at plant stops. While a former study confirmed that conventional and EMAT probes provide very similar thickness data when test surface is clean [3], the real benefit will be testing without surface preparation. Testing on a raw surface will prevent the minimum thickness is reached due to grinding on repeated tube wall positions. Unlucky, industrial exploitation of EMATs is getting slowly due to a probe sensitivity much less effective than conventional probes, need of dedicated pulser/receiver and lacking of standard or “best practice”. The aim of this paper is to provide reference data as well hints to shorten the bridge that prevents the “no-contact” EMAT technology from becoming a standardized thickness gauging in-service inspection methodology.

The measurements carried on aged tubes, and the comparison between EMAT and destructive data, allowed to test a procedure for thickness gauging on oxidised and scaled surfaces. The test results shall enable a faster exploitation of the EMAT “no-contact” methodology for a quicker and cheaper, though much reliable, evaluation of boiler tubes.

1. Thickness evaluation on aged test tubes

In a former test five boiler tube samples (Fig.1) collected from a thermoelectric power plant were considered. The picture shows the tubes “as received”; points where EMAT thickness measures were taken are marked in yellow color.

Fig.1 – Aged boiler tubes considered for evaluation of EMAT thickness gauging from oxidised surfaces.

Following are examples of the gathered EMAT signals. Tubes like "SH2-in" had no scale and less oxide resulting in thinner echoes, detectable at intermediate gain (Fig.2).

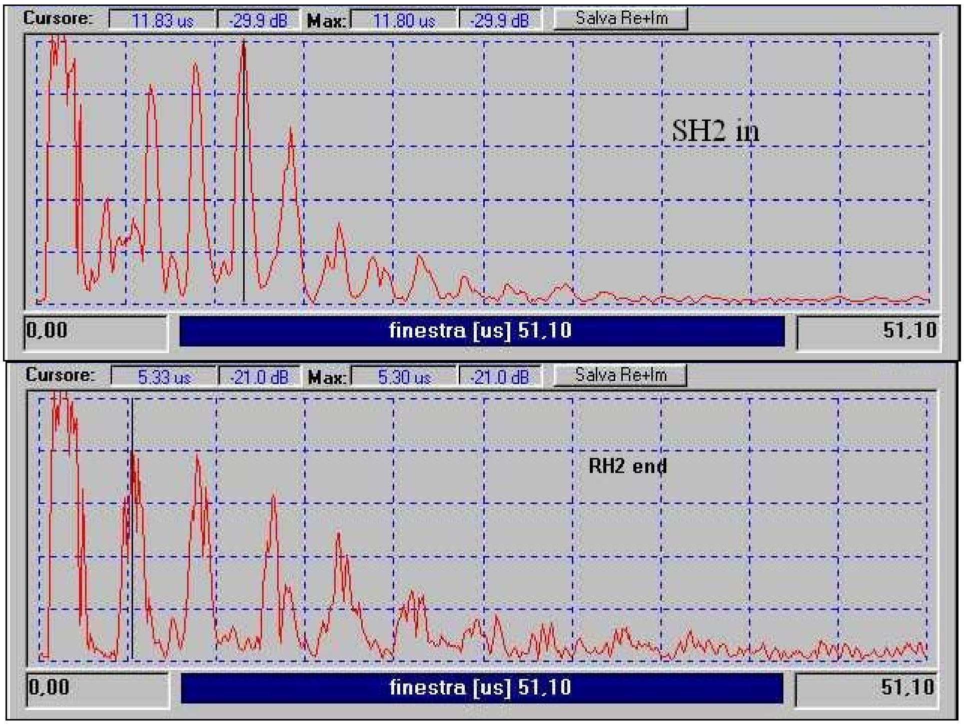

Fig.2 - EMAT test. Upper: tube SH2-in, oxidised without scale. Lower RH2-end, a scaled and oxidised tube.

Echoes with many peaks were recorded from severely damaged tube RH2 (Fig.2). Waveforms changed depending from scale and the oxide thickness on the tube walls at each test point; outer oxide was beneficial to the sensitivity allowing all measures at lower gain.

1.1 EMAT signal analysis

On all 84 points measured and signals recorded, two travel time evaluation methods were exploited according to standard EN 14127: “echo-echo” distance (T1) and “1st echo arrival” (T2). Wave speed and initial time delay were calibrated on a clean carbon steel test piece, respectively v=3.295 mm/μsec and 0.69 μsec at 4 MHz. Initial time delay was subtracted from T2 data before estimating the wall thickness from 1st echo arrival data.

Fig.3 shows a comparison between thickness data evaluated from T1 and T2. Data from echo-echo distance were slightly higher than those from 1st echo arrival. The biggest difference is from tube RH2, suggesting the great oxide thickness on the outer face can heavily influence the test; it is thus possible that the two time evaluations sense different ultrasonic paths when the test, made by an EMAT probe, is carried on aged oxidised tubes.

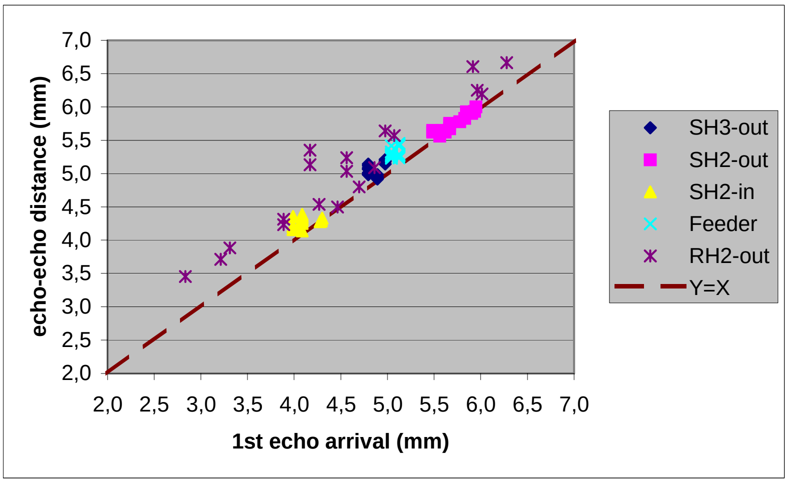

Fig.3 – EMAT thickness data on oxidised boiler tubes: echo-echo distance generally exceeds 1st echo arrival.

The actual path that a signal from an EMAT probe travels when generated on a oxidised surface was thus envisaged. When such probe is placed on a clean magnetic and conductive material, an elastic pulse is generated thanks to the electromagnetic energy radiated from the probe converting into elastic, by means of a Lorentz force mechanism. When on an oxidised tube, the same electromagnetic energy will cross the magnetite, a non-conductive layer of high magnetic permeability, penetrating till to the conductive steel, without phase or time delay. Magnetite will also enable additional energy conversion to empower the signal: while the high induction from the probe polarises the magnetite, the synchronous eddy currents will drive sudden magnetic field reversals and originate elastic oscillations to convert more energy by magnetostriction. The total elastic energy generated will eventually get and comes out from the magnetite / steel interface, travelling the whole tube thickness. Though magnetite is the most active in pulse generation, the pulse will probably have its very start from the steel interface, at the depth that the eddy current field radiated from the probe coil can actually penetrate according to the skin effect.

Fig.4 shows a schematic of the ultrasonic path thus expected in a oxidised tube. The pulse generated after all electromagnetic energy is converted into elastic, starting from the outer oxide / steel interface, will travel inside the layered material, partially reflecting at inner and outer oxide / steel interfaces. Broadening of echo peaks shall probably occur when the thickness of the oxidised layers increase at inside/outside walls.

The aim of the following analysis is thus to evaluate the feasibility of EMAT thickness gauging and, in addition, highlight topics for further investigation so that the better test procedure can be eventually achieved.

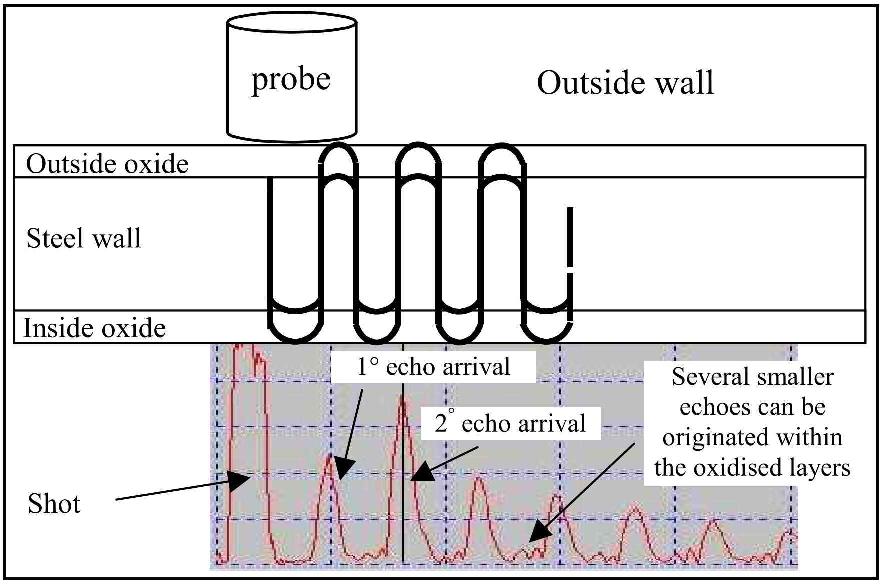

Fig.4 – Schematic of the ultrasonic pulse in a layered material with oxide on inside and outside walls

2. Comparison between EMAT and destructive thickness data

The aged tubes were sent to destructive testing for mechanical evaluation and analysis of microstructure by optic and electron microscopy. Though EMAT data were collected in several sections (4 sections on the straight tubes and 5 on the bifurcated tube), destructive data were collected in each tube at one single section only: this circumstance is to be taken into account when comparing the data and evaluating the test results.

Comparison between thickness evaluated by echo-echo distance (T1) and 1st echo arrival (T2) showed that T1>=T2. Based on Fig.3 we suppose T1 detects the whole tube thickness. Accordingly, T2 detecting the 1st echo arrival shall not include the outer oxidised layer, in which case only the path from steel interface to inside wall is taken into account.

Tab.1 - Destructive data and EMAT thickness in mm (v=3.295mm/µsec)

Reference data		**Destructive data - steel and oxidised layers**				**EMAT data**		
Tubes	**Nominal**	**Whole wall**	**Inner oxide**	**Outer oxide**	**Whole wall - outer oxide**	**T1 echo-echo**	**T2 1st echo**	**T1-T2**
SH2 in	4	4.33	0.065	0.090	4,24	4.19	4.02	0.17
SH2 out	5	5.48	0.220	0.180	5,3	5.66	5.62	0.04
SH3	5	5.16	0.110	0.080	5,08	4.96	4.77	0.19
Feeder	5	5.59	0.035	0.050	5,54	5.22	4.98	0.24
RH2 y1	3.6	4.96	0.720	1.035	3,925	4.45	4.09	0.36

Tab.1 shows nominal, destructive and EMAT thickness data. Mean EMAT data, the average of 16 test points (20 for RH2), represent the whole condition of each tube sample. EMAT data T1 are quite in agreement with the actual whole thickness (steel and oxidised layers); less agreement was found for the most damaged tube RH2, which had much scale and thick oxidised layers outside (and inside) and where the surface condition made the thickness data change very much from point to point. EMAT data T2 were compared to the amount "whole wall - outer oxide layer" or "steel + inner oxide layer", which is the quantity that can be detected by a contact conventional probe. Also in this case there is a reasonable agreement, especially for RH2 data, while larger deviations occur for feeder tube: again, the quality of the agreement must be carefully weighted due to the poor statistics of the data.

Last column T1-T2 shows thickness data that shall evaluate the outer oxidised layer. As too few destructive data were measured, the correlation is tentative, however T1-T2 is not null and that justifies the search of such correlation.

Data presentation was then exploited from all available data. A comprehensive chart was arranged, using mean minimum and maximum thickness data, both from destructive measures (taken at 90° in one single section per each tube) and from EMAT signals (taken at 90° in 4 sections per each tube - 5 sections on RH2).

Fig.5 compares EMAT data T1 (echo-echo) to actual thickness data (whole wall). Differences between mean EMAT and destructive data are up to ±0.2 mm, with both ranges reasonably well superposed; condition of tube RH2 is testified by the large range and the difference between mini./max. of EMAT and destructive data. The quality of T2 data, found quite in agreement to "steel + inside oxide layer", shall be improved to better detect the echo start time: reliably measuring T2 by an EMAT probe on an oxidised surface can be a key step to perform thickness gauging, as much as a conventional contact probe can do only after the surface of the aged tube is cleaned and machined flat.

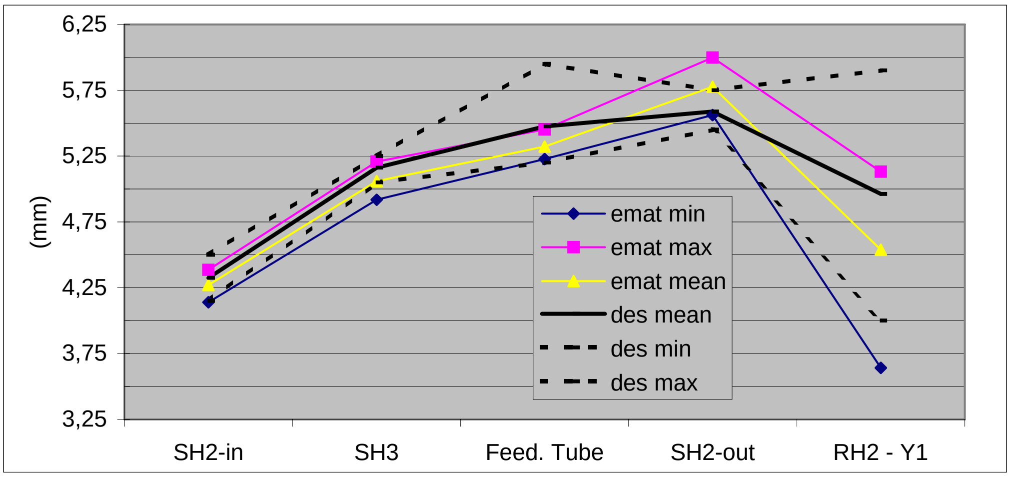

Fig.5 - Comparison between EMAT (echo-echo distance) and actual tube thickness (outer oxide included).

2. Further measures on machined samples

The above results showed the ability of EMAT probes for quick thickness gauging on aged boiler tubes. More tests and reference data would allow better procedures to adequately support the exploitation of the EMAT method in field. Some issues are considered below.

2.1. Physical properties of the oxidised layers

To properly evaluate the contribution of oxidised layers, one should know the elastic properties of magnetite, particularly the suited wave velocity. Magnetite density 5.2 g/cm^3 shall increase wave velocity as compared to steel (7.8 g/cm^3) by 1.2; on one paper a longitudinal wave velocity of 7.4 mm/µsec is reported [4], 1.25 times higher than in steel. This will lead a shear wave velocity of 4 mm/µsec in magnetite, slightly higher than steel.

2.2 Need of specific samples for calibration and test on oxidised tubes

Suitably machined samples (whole thickness, steel + inside oxide, steel + outside oxide, bare steel) allows to test and study all relevant tube conditions, and provide reference data for calibration and test. A piece of aged tube was cut longitudinally in 4 segments, which were suitably clamped for grinding while keeping the cylindrical geometry (Fig.6).

Fig.6 - Tube samples machined for calibration on different wall conditions.

Measured thickness data, mechanical and EMAT, are summarised in Tab.2. Wave speed (3.26 mm/µsec) and initial time delay (about 0.7 µsec) were evaluated on sample n°1 (bare steel).

Tab.2 - Mechanical and EMAT data corresponding to different wall thickness conditions

		Mechanical		**EMAT**
Tube samples & surface condition		**Whole wall (mm)**	**Oxide (mm)**	**T1 echo-echo (mm)**
1	Bare steel	9.1		9.09÷9.2
2	Steel + outer oxide	9.4÷10	0.3÷0.9	9.58÷10.27
3	Steel + inner oxide	10.2	1.1	10.15÷10.17
4	Whole wall	10.5÷11	1.4÷1.9	10.3÷11.05

On sample n°2 more points were tested from the oxidised face. Signals were formerly taken at 4 MHz - 1 burst to shorten as much as possible the echo width. As some not resolvable echoes appeared, frequency was set to 5 MHz so to improve the resolution, allowing more accurate time evaluations on such some test points. T1 gave values in the range 9.58÷10.27, T2 data were found in a thinner range 9.27÷9.47. Difference T2-T1 was found in the range 0.2÷0.93, quite in agreement to the mechanical data (0.3÷0.9) obtained by measuring the thickness a micrometer.

2.3. EMAT sensor / equipment of improved performance for new and aged tubes

Most EMAT systems can test aged boiler tubes, but can be inadequate on new tubes. This prevents NDT users from evaluating baseline thickness or boiler tubing systems. A test solution allowing testing on both aged and new tubes would help EMAT exploitation.

The sensor design should be improved to jump between new and aged surfaces without altering too much the system settings. We compared two different sensor design showing an improvement of 10 dB in case the sensor architecture and characteristics are properly arranged (Fig.7). A better sensor sensitivity will reduce the requirements on the EMAT pulse/receive unit.

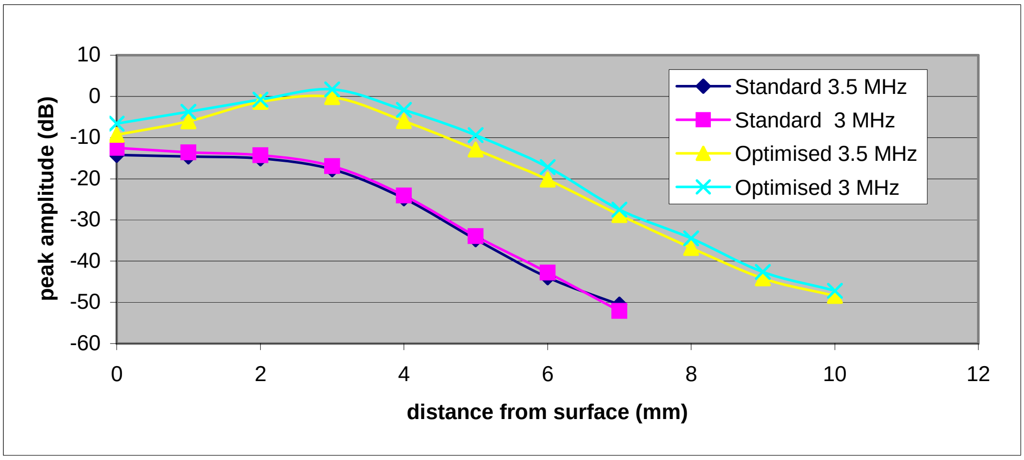

Fig.7 - Comparison of the signal amplitude from two EMAT probes of different design on an aged tube.

The test frequency is a key parameter to characterise oxidised layers, particularly the inside layer whose thickness shall be kept as low as possible to improve thermal exchange between the hot gases and the steam. 4 MHz test frequency, suited to measure the whole thickness, is too few to detect thin oxidised layers. Fig.8 shows the half wavelength of a shear wave vs. test frequency. At 4 MHz resolution is 0.4 mm, quite in agreement with the performance recorded in our tests. To detect oxidised layers thinner than 0,1 mm the test frequency should go up to 10 MHz. Luckily, magnetite can keep a favourable sensor sensitivity to work on aged tubes at such higher test frequencies.

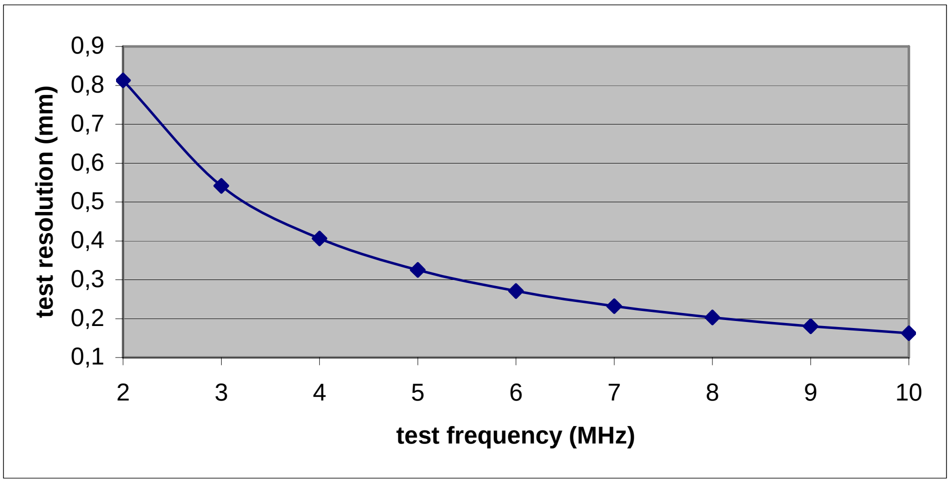

Fig.8 - A EMAT system operating at up to 10 MHz would evaluate oxidised layers lower than 0.1 mm.

The CESI system Ecomat-TH can test on aged and new surfaces, though its main limitation is the need of a computer platform. A pulser driven on a tone burst mode and a sensitive receiver are mandatory for an effective EMAT test system. Today powerful digital components are increasingly available and we expect that equipment of updated design will further help exploiting the EMAT methodology in the future.

The potential of EMAT thickness gauging can even be improved by a remote automated test configuration. CESI has developed a wheeled carriage to scan waterwall surfaces, which can host a camera for visual inspections of burners (Fig.9), or an EMAT kit to evaluate thickness of waterwall tubes [5]. Such kind of system architecture, working with wired or wireless connection, will allow much faster remote automated thickness tests inside the boiler chamber of fossil fuelled thermoelectric power plants.

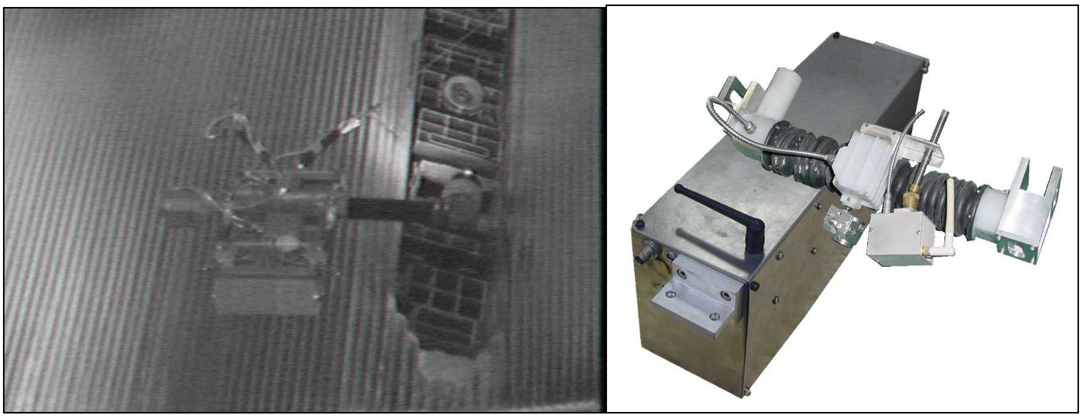

Fig.9 - A waterwall climbing robot for visual inspections (left) and the EMAT kit for thickness gauging.

Conclusions

EMAT "no-contact" probes can test the thickness of aged oxidised boiler tubes. A test was carried to study the reliability and potential of such solution, and suggest procedures to better exploit EMAT thickness gauging in plant maintenance tests. Two standard methods were considered for travel time evaluation. EMAT and destructive data agreed within ±0.2 mm in evaluating the wall thickness by echo-echo distance. The results suggest the accurate detection of 1^{st} echo arrival time can evaluate the "steel + inside oxide" thickness by using the EMAT probe on aged oxidised tubes. Further developments were evaluated as to sensor design. Equipment for testing at higher frequency will help discriminating between steel and inside oxide, a substantial breakthrough as compared to standard thickness gauging. Exploiting EMAT sensor and equipment solution in remote tests by means of a waterwall climbing carriage, would eventually eliminate the need of scaffolding, shorten the test time, and ensure a better thickness evaluation of boiler waterwall tubes.

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