Ultrasonic Thickness Measurement of Internal Oxide Scale in Steam Boiler Tubes

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Abstract: Accurate measurement of the thickness of internal oxide scale in steam boiler tubes is an important factor in predicting tube life. This paper discusses ultrasonic techniques for nondestructive scale thickness measurement with small, portable instruments.

A significant limiting factor that affects tube life in fossil fired steam boilers is the growth of iron oxide scale (magnetite) on the inside and outside tube surfaces. The oxide scale, which forms under long term exposure to very high temperatures, acts as a thermal insulator. While external scale limits heat transmission into the tube and reduces boiler efficiency, internal scale buildup represents a potentially more serious problem. The insulating effect of internal scale limits heat transmission into the water vapor inside the tube, which in turn causes chronic overheating of the tube wall and promotes accelerated metallurgical failure.

Nondestructive measurement of internal oxide scale thickness is of major interest in the power generation industry and other users of fossil fuel steam boilers, since scale thickness may be used to predict remaining tube life. While very high frequency ultrasonic gaging techniques have been available for this measurement for a number of years, they involved use of cumbersome, expensive pulser/receiver and oscilloscope systems. Recent advances in instrumentation technology have made available small, hand-held ultrasonic gages with software optimized for measurement of internal scale and advanced data logging capability. Additionally, the use of normal incidence shear wave transducers improves resolution of thin scale layers, permitting measurement of scale buildup down to approximately 0.125 mm with hand-held equipment.

This paper will discuss the importance of reliable measurement of oxide scale system, discuss current nondestructive measurement options, and describe the instruments and ultrasonic transducers that have been developed for this purpose.

Background

The very high temperatures found inside steam boilers (in excess of 1500 degrees Fahrenheit or 800 degrees Celsius) can cause the formation of a specific type of hard, brittle iron oxide called magnetite on the inside and outside surfaces of steel boiler tubing. At very high temperatures, water vapor will react with the iron in the steel to form magnetite and hydrogen according to the formula:

$$3\ Fe + 4\ H_20 = Fe_3O_4 + 4\ H_2$$

The speed of this reaction increases with temperature. Oxygen atoms will diffuse inward through the magnetite layer, and iron atoms will diffuse outward, so the scale continues to grow even after the tube surface is completely covered [1].

Magnetite scale acts as thermal insulation on the pipe, since the thermal conductivity of scale is only about 5% that of steel. When heat can no longer transfer efficiently from the flame through the tube into the steam inside, the tube wall will heat up to temperatures beyond the intended operating range. Long term exposure to overly high temperatures, combined with the very high pressure inside the tube, leads to intergranular micro-cracking in the metal and to creep deformation (a slow swelling or bulging of the metal), which in turn eventually leads to tube failure by bursting. A secondary issue is oxide exfoliation, in which pieces of oxide scale break off (usually due to thermal stresses during boiler startup or shutdown). These hard pieces will be carried by the steam flow into the turbine, where over time they will cause erosion damage.

The growth of magnetite scale and the associated metal damage are primary limiting factors with respect to boiler tube service life. The process begins slowly and then accelerates, for as the scale grows thicker the tube wall becomes hotter, and that in turn increases the rate of both scale growth and metal damage. Studies in the power generation industry have indicated that the effect of scale is relatively insignificant up to thicknesses of approximately 0.3 mm, but that beyond that thickness the negative effects of scale increase rapidly [2]. Periodic measurement of scale thickness allows a plant operator to estimate remaining tube service life and replace tubes that are approaching the failure point.

Ultrasonic Instrumentation and Transducers

Ultrasonic pulse/echo thickness measurement techniques have been used for internal oxide scale measurement for many years. Early documentation of this test frequently involved use of very high frequency ultrasonic transducers and pulser/receivers, with pulse transit time measured by means of an oscilloscope [3]. These systems were effective as regards measuring scale thickness, but not convenient for field use, and expensive as well. Simple ultrasonic corrosion gages designed for measurement of remaining wall thickness with dual element transducers cannot measure oxide layers because of insufficient axial resolution related both to the ringing narrowband waveforms associated with duals and typical signal processing techniques.

The solution lies in handheld ultrasonic thickness gages that can be used with relatively high frequency (20 MHz) broadband, single element transducers, and that incorporate software that is capable of detecting appropriate echoes and measuring the short time interval between the two echo peaks that represent the steel/oxide and oxide/air boundaries, as seen below. As in any ultrasonic gaging application, the instrument measures the time intervals between relevant echoes and then uses a calibrated sound velocity value to calculate thicknesses . **Figure 1** shows typical measurements of thick and thinner oxide. The tube wall thickness is also measured and displayed. In the waveform at left, the large echo at the left side of the screen represents the outside surface of the tube, the smaller peak at the right side of the screen represents the steel/oxide boundary, and the large echo at right represents the inside surface of the oxide.

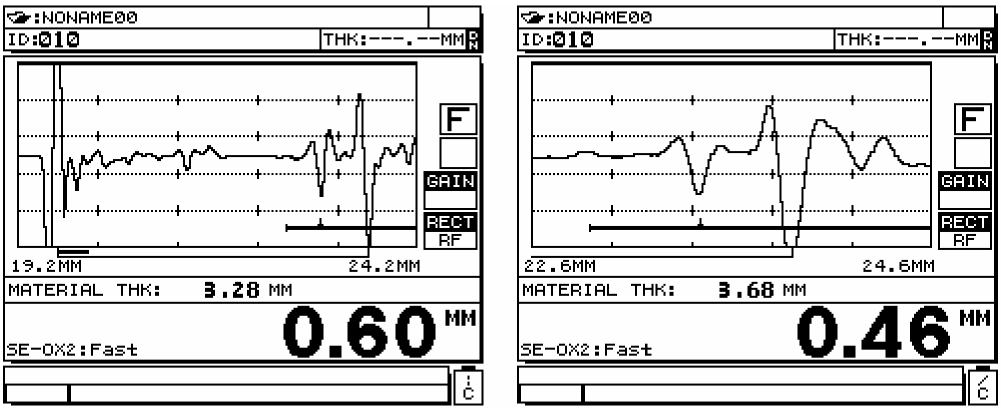

Figure 1. Typical internal oxide measurements with Panametrics-NDT Model 37DL PLUS thickness gage using 20 MHz transducer. Waveform on right has been zoomed to show details of oxide echo shape.

Because of the relative acoustic impedances of steel, oxide, and air, the steel/oxide echo will usually be smaller than the oxide/air echo, as seen here. The internal oxide layer must be bonded to the tube wall. In cases where thick oxide has exfoliated, there will be no acoustic coupling between the steel and oxide and thus ultrasonic thickness measurements will not be possible.

Common contact and delay line transducers used in ultrasonic thickness gaging generate and receive longitudinal mode waves. Delay line transducers offer the advantage of removable plastic delay lines that can be inexpensively replaced when scratched or worn. Using typical commercial 20 MHz transducers, oxide can usually be measured down to a minimum thickness of less than 0.25 mm. However, that minimum can be further reduced through the use of normal incidence shear wave transducers. Because shear wave velocity in metals and hard oxides is approximately 60% of longitudinal wave velocity, the minimum possible time resolution in a shear mode will be reduced by an equal percentage. In the specific case of oxide scale measurements, 20 MHz delay line type normal incidence shear wave transducers can measure scale layers as thin as 0.125 mm. Note that shear wave transducers must be used with special high viscosity shear wave couplants. Additionally, transducers must be coupled to a relatively smooth outside surface. In situations where the outside of the tube is rough or covered with loose deposits, surface preparation will be required. **Figure 2** shows a measurement of thin oxide scale (and tube wall thickness) using a shear wave delay line transducer, and the characteristic single peak associated with disbonded oxide or oxide not present.

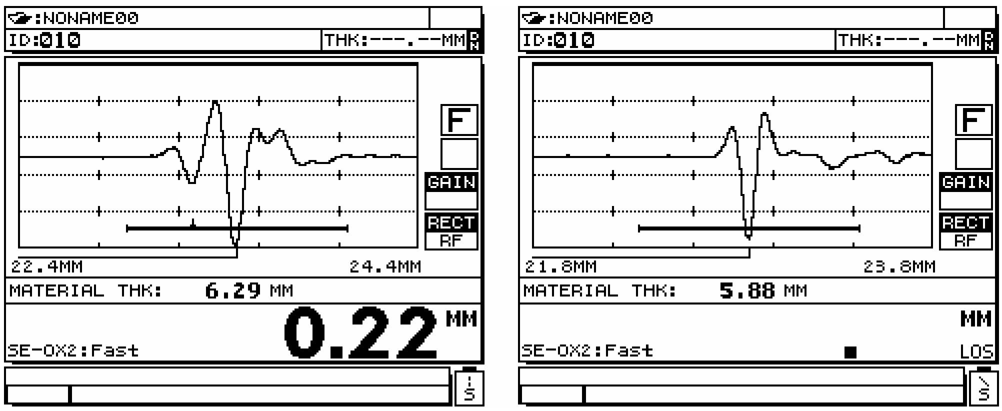

Figure 2. Shear wave measurement of thin oxide (left) and single peak tube wall waveform associated with disbonded oxide or oxide not present (right).

It is also possible to measure oxide layers with portable ultrasonic flaw detectors that have sufficient RF bandwidth (>20 MHz) and the capability to display an unrectified waveform. Some instruments have available software options that will simply the necessary peak-to-peak measurement, as seen in **Figure 3** below.

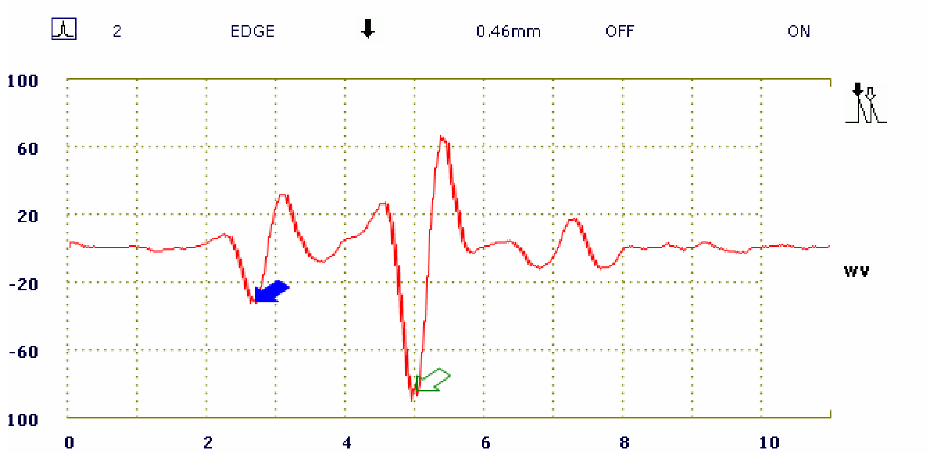

Figure 3. Typical internal oxide measurement with Panametrics-NDT EPOCH 4 flaw detector and 20 MHz normal incidence delay line transducer. Scale thickness is 0.46 mm.

A third category of instrumentation that has been used for oxide measurement is high frequency pulser/receivers with RF bandwidths of 75 MHz or greater, used with transducers of frequencies up to 50 MHz. These instruments are used with either an oscilloscope or a computer with a waveform digitizer and appropriate software. The advantage of high frequency pulser/receivers is that oxide layers as thin as 0.1 mm or less can be measured. However this sort of equipment is less portable than thickness gages or flaw detectors, and testing boiler tubes at 50 MHz requires careful surface preparation to insure proper sound coupling. **Figure 4** shows measurement of 0.105 mm oxide at 50 MHz using a 200 MHz bandwidth pulser/receiver and a digital wave analysis program. This instrument displays the steel/oxide and oxide/air echoes as positive peaks.

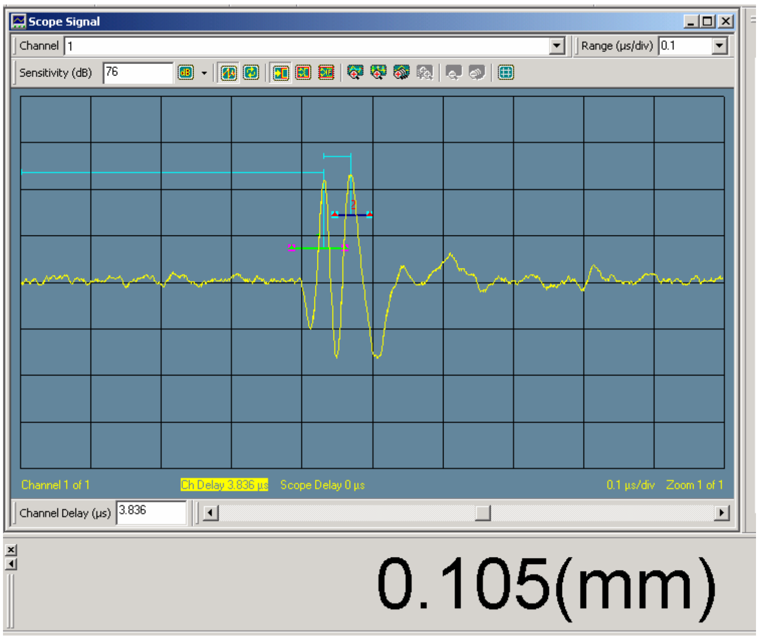

Figure 4. Measurement of 0.105 mm oxide scale with 50 MHz delay line transducer.

Conclusion

Measurement of thin layers of internal oxide scale in steam boiler tubes is an important tool for predicting remaining tube life. Modern ultrasonic instruments offer measurement capability that is quick, accurate, and reliable.

Notes:

[1] French, David N., *Metallurgical Failures in Fossil Fired Boilers*, John Wiley & Sons, New York, 1983, pp. 143-145.
[2] R. Viswanathan, *Damage Mechanisms and Life Assessment of High-Temperature Components*, ASM International, Metals Park, OH, 1989
[3] US Patent 4,669,310 (1987)