ON THE ACCURACY OF A.C. FLUX LEAKAGE, EDDY CURRENT, EMAT AND ULTRASONIC
METHODS OF MEASURING SURFACE CONNECTING FLAWS IN SEAMLESS STEEL TUBING

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INTRODUCTION

The objective of this study was to perform a comparative experimental evaluation to determine the detection sensitivity, classification (flaw type) and depth sizing accuracy of A.C. flux leakage, single-frequency eddy current, electromagnetic acoustic transducer (EMAT) generated surface waves, and broadband ultrasonic methods for the measurement of complex surface connecting flaws in hot rolled, seamless, ferritic tubing. Since it was of interest to invest NDE techniques over a wide range of capabilities, tubing having flaw depths far exceeding industry standards was tested and evaluated. Results of the study will be used to provide a benchmark assessment of these NDE methods, from which decisions concerning production test systems can be made.

A.C. flux leakage and single-frequency eddy current methods are state-of-practice technologies used for production testing of tubular products. A prototype EMAT system was used to generate surface waves around the tube circumference. Transmit and receive EMATs were used to detect and measure flaw depth using the signal attenuation technique. A broadband ultrasonic system was used in the laboratory to profile the depth of flaws using time-of-flight information. This ultrasonic technique was used to measure flaw depth in attempts to develop a flawed tube specimen matrix having good statistical distribution.

On completion of testing with the above NDE methods, the true flaw parameters were obtained through extensive metallographic examination of selected regions of these tubes. This paper presents the results of this comprehensive study.

OUTER DIAMETER SURFACE CONNECTING FLAWS IN SEAMLESS TUBING

The seamless steel tube making process is achieved by piercing hot round billets using double conical rolls as shown in Figure 1. There are complex processing stages involved in the making, shaping, heat treating, conditioning, forming, and finishing of steel products. This complex manufacturing process is constantly being upgraded with technology improvements.
Figure 1. (a) Piercing operation using double conical rolls to make seamless steel tubing from round hot billets. (b) Change of flaw type (seam to lap) in piercing operation.

Two types of surface connecting flaws in seamless tubes that are unacceptable when their depth exceeds an established cleanup machining limit are termed lap and seam flaws. Figure 2 shows metallographic examples of these flaws.

Figure 2. Metallographic example of lap and seam type surface connecting flaws.

Quality control requirements dictate that the nondestructive testing system for seamless tubes have good detection reliability, accurate sizing, high throughput, and flaw classification capability.

FLUX LEAKAGE AND EDDY CURRENT TESTING

Leakage flux methods of nondestructive testing are based on the interaction of a magnetic field with a flaw to identify the existence of a flaw, its size, and location. Because of the higher magnetic reluctance property of a flaw in a magnetic circuit, flux lines will take the lowest reluctance path in a fully or nearly saturated magnetic circuit [1]. Thus, a flaw could cause magnetic flux lines to propagate (leakage flux) across the surface connecting section of the flaw as
shown in Figure 3. For the O.D. inspection of ferritic tubular products magnetic saturation can be achieved in two different ways (alternating current or direct current excitation) as shown in Figure 3. Two A.C. flux leakage systems (system-A operates at 3 KHz

![Diagram of D.C. and A.C. magnetic fields](image)

Figure 3. Topographical features of D.C. and A.C. magnetic fields around a flaw in a magnetic material.

and uses induction coils, and system-B operates at 2 KHz and uses magnetodiodes) were considered for evaluation in this study.

Three foot long sections of tubes were tested using A.C. flux leakage and single frequency eddy current methods. A prototype laboratory system using production heads and instruments is shown in the simplified sketch of Figure 4. A lathe was used to rotate the tubes at desired speeds, while a sensor mounted on the lathe carriage scanned the tube O.D. longitudinally. This approach to material handling of the tube simulates industry practice. The other common approach uses rotating sensors, while the tube traverses past the sensors.

![Diagram of A.C. and D.C. fields](image)

Figure 4. A prototype laboratory inspection system for recording O.D. flaw signals.

Two single-frequency eddy current systems (system-C operating at a test frequency of 300 KHz, and system-D at 250 KHz) were evaluated. Figure 5 shows typical strip chart recordings of the 3 KHz A.C. flux leakage amplitude information (system-A) compared with the 300 KHz eddy current (system-C) amplitude information. The reader will note the dramatic change (i.e. signal peak to valley transitions) for the A.C. flux leakage case. This is likely attributed to the variation in crack closure at the surface of the tube. If the crack is tight, or closed at the surface, leakage of flux is minimum. This leads to questions regarding detection reliability. Figure 6 shows a photomicrograph of a tube wall section having two seam type cracks near one another. Crack (a) is 0.05 inches in depth and has a wide crack opening at the tube wall.
Figure 5. Typical strip-chart outputs from (a) system-A (3 KHz A.C. flux leakage) and (b) system-C (300 KHz eddy current) for the same tube.

Figure 6. Photomicrograph of surface connecting flaws in a seamless tube specimen.

surface relative to crack (b). Crack (b) is 0.152 inches in depth and tight at the surface. A.C. flux leakage testing (system-A) produced amplitude information that resulted in a flaw depth measurement of 0.014 inches. It appears that crack (a) (with the wider opening of crack at the surface), caused the flux to leak, whereas crack (b) was a low reluctance path with minimum leakage flux.

From Figure 5, it is easily discernible from the recordings, if flaw signal amplitude is the measure of flaw depth, system-A and system-B do not indicate the same flaw depth variation along the tube length. In a separate investigation, it was observed that eddy current amplitude information followed the flaw depth profile consistently, and appeared not to be sensitive to flaw tightness at the O.D. surface (Figure 5).

EMAT TESTING

The basic operating principles of an EMAT are illustrated in Figure 7. In its most elementary form, it consists of a single wire carrying an alternating current I. An eddy current density J is induced in the surface of a metal object in close proximity to the wire. In the presence of a strong static magnetic field H, Lorentz forces are experienced, causing an acoustic wave M, to be generated whose frequency is that of the induced eddy current. The acoustic wave is detected by the reciprocal process.
Figure 7. Single wire model used to illustrate the basic operating principles of an EMAT.

Figure 8 shows the configuration of EMATs, magnets, and tube used for collecting experimental data. The EMATs were mounted on a flexible plastic wear sheet (5-mils thick) and backed with a compliant sponge-like material so that the EMAT could easily conform to the curvature of the tube surface. Two EMAT coils of desired frequency were laid end-to-end in the gap between the pole pieces of both magnets. The magnetic field was tangential to the surface of the tube, thus generating a surface wave. This arrangement allowed both pulse-echo and through transmission modes of testing to be performed. Figure 9(a) shows a typical strip chart recording from artificial slots for pulse-echo and through transmission operating modes.

Due to the complex geometric characteristics of the surface connecting lap and seam flaws, the pulse-echo mode proved to be unreliable for detection. The sound energy is redirected away from the sensor. However, the attenuation mode proved to be very reliable. Figure 9(b) presents the results of both theoretical calculations and experimental measurements for frequencies of 2400 KHz, 1200 KHz and 800 KHz transmitted around a narrow slot [2]. The flaw depth is given as a function of the relative signal amplitude ($A_T/A_0$).

BROADBAND ULTRASONIC TESTING

A broadband ultrasonic transducer and pulser-receiver system was used to measure surface connecting flaws via the pulse-echo technique. A highly damped focused transducer was used to produce a time limited broad bandwidth pulse. The transducer acoustic beam was aligned normal...
Figure 9. (a) Example of strip chart output showing direct transmission signal (upper trace) and pulse echo signal (lower trace). 
(b) Signal amplitude transmitted through a slot at three different frequencies as a function of the slot depth.

to the tube surface and focused at the surface. Time-of-flight measurements were used to determine B-scan type information that determined the depth profile of the flaw, and a means to characterize the flaw as being either a lap or seam (see Figure 2).

Broadband ultrasound time-of-flight measurements were thought to be the best quantitative means for measuring the depth of lap and seam flaws, with qualification. Lap and seam flaws less than 0.040 inches in depth are often difficult to interpret due to front surface echo interference, weak flaw signal response due to flaw geometry, redirectivity of the sound field, and misinterpretation of a second or third multiple reflection as being the true flaw depth.

COMPARISON OF MEASURED FLAW DEPTH WITH TRUE FLAW DEPTH

Comparing test results for system-A through system-F, tube sections were chosen for destructive determination of true flaw parameters. Extensive metallographic work was performed on large numbers of tube sections (over 500 flaw cross-sections) to determine the complexity of the flaw along the tube axis, and to measure the true depth accurately. In most cases flaw cross-sections were photographed every 0.05 inches along several inches of the tube axis. Flaw depth was measured as the radial distance between the O.D. surface and the deepest discontinuity in the tube wall. Signals from artificial slots (e.g. Figure 5) were used to "calibrate" the A.C. flux leakage and eddy current inspection systems. The slots were also used in determining the depth of natural flaws from strip chart information. The EMAT-surface acoustic wave method used the theoretical curve (800 KHz) of Figure 9(b) to determine flaw depth. System gain was set so as not to saturate flaw signal information. The broad band ultrasonic system was calibrated using precision thickness blocks of the same steel type as tube specimens. Nondestructively measured depth vs. true flaw depth
is compared in Figure 10 for each inspection system considered for evaluation.

CONCLUSION

Figure 10 shows the results from A.C. flux leakage, eddy current, EMAT, and broadband ultrasonic methods for the depth measurement of surface connecting flaws in seamless tubes. Not all the tube samples were tested by every NDE system under evaluation (A through F in Figure 10). Hence the reason for unequal number of data points between graphs in Figure 10.

The A.C. flux leakage measurements tend to consistently underestimate the flaw depths exceeding 0.040 inches. Careful review of the flux leakage data suggests that these deeper flaws are beyond the active flux field boundary. The reader will note for system-A, that there are two data points between 0.12 inches and 0.14 inches (horizontal axis) where flaws of this depth were not detected. This was attributed to the crack being very tight at the surface. One can observe that there are many other data points between 0.08 inches and 0.16 inches where the detection sensitivity of flaws was minimal. Flaws less than 0.040 inches also tend to be underestimated. There were five data points between 0.010 inches and 0.020 inches where flaws of this depth were not detected. Between 0.030 inches and 0.050 inches there are six data points where flaw detection sensitivity was minimal. From the above observations, there is uncertainty in making an assessment of the measurement accuracy of A.C. flux leakage for flaws less than 0.04 inches in depth. From the data, the more important question becomes one of detection reliability. Review of the metallographic data for those flaws not detected showed the cracks to be tight at the surface. Our system design requirements demand that the system have high detection reliability and the best possible sizing accuracy for flaws up to 0.12 inches deep. One might suggest using D.C. flux leakage to provide flux fields that saturate the wall thickness, thus achieving the required dynamic range. However, one still has the problem of detection reliability with tight crack conditions whether the A.C. or D.C. flux leakage method is used.

The eddy current measurement results shown in Figure 10 are similar to the A.C. flux leakage results. System-C showed minimum detection sensitivity for some flaws between 0.02 inches and 0.04 inches. Eddy current measurement results were obtained using differential coil probes. A best case calculation of "standard depth of penetration" at 300 KHz was 0.017 inches. Realistically, the actual "standard depth of penetration" can be less, due to limited probe diameter. Therefore, flaws greater than 0.045 inches would be measured as being no greater than 0.045 inches, as is shown for system-C.

Figure 10 (system-E) shows the results obtained using electromagnetic acoustic generated surface waves (Rayleigh) at an excitation frequency of 800 KHz ($\lambda = 150$ mils). The results are based on attenuation of signal, and show good detection reliability and sizing accuracy. There are five data points between 0.060 inches and 0.080 inches (horizontal axis) that resulted in overestimating flaw depth. This was thought to be caused by coarse surface conditions that would add to the attenuation measurement, and therefore, result in a conservative estimate of flaw depth. Surface conditions of seamless tubes are generally very good. An on-going empirical study on the effect of flaw angle ($\theta$ in Figure 11) showed that the energy transmitted past a flaw seems to depend only on flaw depth and not on
Figure 10. Graphs showing flaw depth measurement accuracy for each NDE system.
angle \(0 < \theta < \pi\) [3]. Further testing of defective tube specimens is underway, with the goal of demonstrating improved sizing accuracy at a test frequency of 400 KHz (as would be interpreted from Figure 9(b)). Figure 10 shows the results obtained using the broadband ultrasonic (system-P) method where time-of-flight measurements determine flaw depth. Difficulties encountered in attempting to measure flaws under 0.040 inches in depth have previously been discussed. For flaws greater than 0.040 inches, the data shows the broadband ultrasonic method having good detection reliability and the best sizing accuracy. Furthermore, it allows for the generation of a B-scan image that is used to classify the flaw as lap or seam.

In summary, the broadband ultrasonic method of evaluation offers three important performance capabilities for a nondestructive test system—detection, sizing, and flaw type classification. Systems of this type are yet to be developed for mill inspection. The EMAT-surface acoustic wave method also demonstrated good detection sensitivity and depth sizing accuracy. An EMAT based test system would provide high throughput rates with 100 percent inspection coverage. A flux leakage system developed with a better understanding of field/flaw interaction through numerical modeling techniques, and/or application of multiple-frequency, multiple-parameter eddy current system would offer more measurement capability to address the problem of detection sensitivity, sizing, and flaw classification.

REFERENCES