MEASUREMENT OF LAYERED CORROSION WITH COMPTON BACKSCATTER

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INTRODUCTION

Compton backscatter has intrigued NDT researchers for a number of years because of its capability for making x-ray pictures without requiring access to both sides of the piece being examined[1]. The major obstacles to commercial development have been its slowness and the high cost of the equipment. Additionally, the resolution obtained has been circumscribed; the best reported resolution appears to be less than 1.5 lp/mm.[2]. As a result, little commercial application has emerged for Compton backscatter as an imaging tool. Recently, interest in aircraft corrosion has renewed interest in Compton backscatter for NDT. This interest appears to be justified partly because aircraft corrosion often takes a layered morphology; and, the needed information is the thickness of the layers. Consequently, it is possible to trade resolution in the directions whose axes lie in the plane of the layers for better resolution along the thickness axis. Furthermore, because the layers usually have a lateral extension of several inches or more, the measurement problem can be reduced to a one dimensional scan in the thickness direction. These characteristics allow for a great reduction in the complexity of the apparatus, a substantial improvement in resolution and an increase in the speed of measurement.

Many means are available for the detection of corrosion in aircraft. But, once corrosion is detected, it remains to determine its severity. FAA directives require that repairs be made if the metal loss exceeds 10% of its thickness. At the present time, the threshold of detection for metal loss is not much less than that. Consequently, all corrosion which is detected generally needs repairing. In order to ascertain metal loss precisely, aircraft owners are obliged to dismantle portions of their planes. In the case of wing or fuselage skins, this usually means drilling out rivets and plastically deforming the sheet metal in prying it apart. This is what gives impetus to the x-ray method. I will describe a Compton scanning device which has measured the thickness of aluminum

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1993

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sheets to an accuracy of 0.001" in most cases. It has also distinguished corrosion products from aluminum giving a 2:1 contrast ratio between them.

DETECTION OF CORROSION

The detection of corrosion by Compton backscatter is dependent upon the difference between the effective electron density in the corrosion product and in the parent aluminum. Some experimental values for these have been tabulated for radiation at energies typical of tungsten radiation at 100 to 150 kV. tube operating voltage[3]. The values obtained for the corrosion product are surprisingly low. Since the energies available are mostly higher than the K-shell energies, one would expect that the effective electron density would be approximately the total sum of core, valence and conduction band electrons. But, the total electron density for several corrosion products in crystalline form, corundum, bayerite, hydra-argilite and diaspore, is very close to that of aluminum itself. Fortunately, corrosion products are seldom crystalline[4]. More importantly, all samples obtained of aluminum corrosion products were porous. It is this porosity which lowers their electron density and permits distinguishing aluminum from them. It is not known whether all such products are sufficiently porous to permit detection.

The need to detect corrosion exists mostly as a byproduct of the need to distinguish corrosion from metal so that the metal can be measured. On the basis of counting statistics alone, it was shown that 14 counts would be adequate to distinguish one from the other accurately[3]. But, actually that is not the whole problem. An associated problem arises from the physical limitations placed upon aperture dimensions. Slit apertures smaller than about 0.002" become difficult to construct for energies on the order of 150keV. because even tungsten is somewhat transparent at these energies. By the geometrical argument given previously [3], the effective scanning aperture size is at least twice that amount. Consequently, some sort of deconvolution is required in order to obtain a measuremant accuracy of 0.001". Perhaps the simplest form of this deconvolution is to fit a convolved boxcar function to each apparent layer. This will be discussed further later on in this paper.

The uncertainty can be estimated for the simplest form of boxcar fitting, that where only a single isolated layer is measured. If we assume that the uncertainty is described by Poisson statistics and that the number of counts is sufficiently high that these may be approximated by a normal distribution, then the 95% confidence interval ranges from plus two standard deviations from the mean to minus two standard deviations from the mean; it is thus four standard deviations in breadth where each standard deviation is equal to the square root of the number of counts. It follows then that the required number of counts to obtain a given uncertainty, Δx, in the measurement of a layer (having two sides) is approximately

$$h = 2(\frac{2w}{\Delta x} (1+\sqrt{2}))^2 \qquad (1)$$

where w is the width of the scanning aperture in the material and h is the required number of counts for the amplitude of a narrow boxcar. Applying this formula to the system being described gives 1165 counts per voxel for 0.001" allowable error and a scanning aperture width of 0.005".

DESCRIPTION OF THE SYSTEM

The imaging portion of the system is described in Fig 1. A slightly diverging beam is formed by apertures 1 and 2. This beam enters the material with normal incidence and is scattered in a roughly isotropic fashion over its entire length. A portion of the scattered beam is selected by apertures 3 and 4. The intersection of the incident path and the selected path for scattered radiation forms a scattering volume 0.20"x0.012"x0.005" in size. Because the scattering angle with respect to the incident beam is 79 degrees, the smallest dimension is in the thickness direction By making the volume element larger in two of its directions, the throughput is increased a factor of ten over what it would have been were the volume element a cube 0.005" on a side. The selected beam falls upon a thallium-doped sodium iodide scintillation detector placed outside aperture 4. The imaging portion of the system, or the camera, is mounted on a positioner which scans it in a direction perpendicular to the surface being examined. The dimensions of the various portions of the system are given in table 1.

DATA PROCESSING AND INTERPRETATION

There are two steps involved in converting raw scan data into useable results, reconstruction and edge-finding. Reconstruction is the process by which the effects of absorbtion are removed from the data. The desired result is a picture of how the scattering cross-section varies from point to point within the material. It is the scattering cross-section which allows identification of the various layers. The scattering cross-section of an air gap is essentially zero. That of aluminum is relatively high while that of corrosion products is about half that of aluminum.and so forth. But, the output signal from the scanner is a function not only of the scattering cross-section at the point where the measurement is made, it also depends upon the absorbtion of the beam on entering to and again on leaving from the scattering zone. During this passage it goes through layers which are often quite different in their characteristscs from the one being examined.
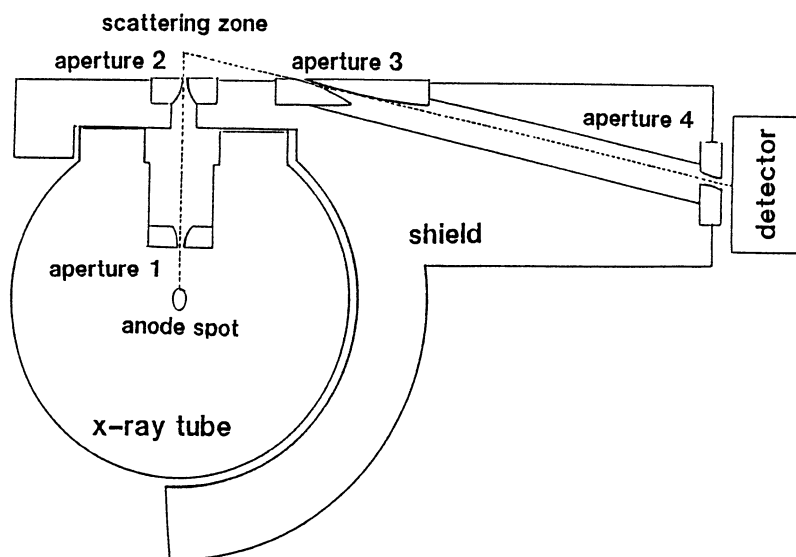

Fig . 1. Geometry of imaging portion of Compton backscatter system.

Reconsruction recovers the scattering cross-section separating it from these other effects. Edge finding is the process by which the interfaces between the various layers are located. This process is, in effect, one of deconvolving the aperture from the data.

Because corrosion and metal layers have a comparitively large lateral extent, it has been possible to treat the reconstruction problem as one-dimensional. This makes the task almost trivial in comparison with reconstruction in computed tomography. Here one merely approximates the linear absorbtion coefficient by making it proportional to the scattering cross-section. This, however, is only an approximation. This approximation may take two forms:

$$\sigma_n = \frac{O_n}{\prod_{(i)}^{n-1} (1-\gamma\sigma_i)} \qquad (2)$$

$$\sigma_n = \frac{O_n \, \sigma_{n-1}}{O_{n-1} \, (1-\gamma\sigma_{n-1})} \qquad (3)$$

Table 1. System Dimensions and Parameters

Source x-ray tube anode spot size: 4mm. x 4 mm.
First aperture: located 1" from anode spot
        dimensions: 0.03" x 0.50"
        material: tungsten

Second aperture: located 2.6" from the anode spot.
        dimensions: 0.006" x 0.12"
        material: tungsten

Scattering angle: 79 degrees

Third aperture: located 1.4" from the scattering volume.
        dimensions: 0.002"(effective) x 0.75"
        material: tungsten.

Fourth aperture: located 3.5" from the third aperture.
        dimensions: 0.012" x 1.5".

System Throughput: 150 counts per second under these conditions.
        Tube Voltage = 155 KV.
        Tube Current = 18 mA.
        Scattering Depth = 0.25" in from the surface, type 6061 Al.
        Background Count = 1 per second with sample removed.
        PMT and SCA settings are for the broadest energy band possible consistent with this background count.
        Note: Throughput and background count measurements were made with Solon 6she3m/2 scintillation detector. Source was Lohmann type 160 ADF tungsten target tube.

where σ_n is the scattering cross-section at the n-th data point counting from the outer surface, O_n is the scanner's output count for the n-th data point, and γ is the constant of proportionality. Equation (3) is more flexible than Eq. (2) but tends to accumulate noise into the signal. The major difficulty with reconstruction based on these equations is that γ is not constant but varies with the composition of the layers and with the energy spectrum of the beam at the point where scattering takes place. Since this spectrum tends to narrow toward higher energies as the beam passes through more material, it effects are termed the beam hardening problem.

The coefficient, γ, is typically constant within a factor of three so long as the operating conditions are constant. Beyond that, it is customary to adjust it so that the scatering cross-section of the innermost layer of aluminum is equal to that of the surface layer. In some tests, screeds, actual pieces of reference material, are glued to the front and back of a sample in order to allow γ to be set so that the average slope of scattering cross-section vs. distance is zero. Nevertheless, this does not solve the beam hardening problem. When the outer layers are being measured, the beam contains a large number of low-energy photons. Many of these are absorbed in photoelectron emission processes and not scattered. Gamma initially tends to under-compensate absorbtion. On the other hand, when the innermost layers are measured, the beam is filtered by the intervening material and has a much higher average energy per photon. The relative probability of photoelectron absorbtion is correspondingly reduced. As a consequence, γ tends to overcompensate for absorbtion. in that region. These compensation errors can become quite large if γ is not adjusted on a scan-by-scan basis. Multiple scattering also makes a contribution to this problem.

When γ is adjusted on a scan-by-scan basis as described above, it has been noted that for scans in solid aluminum, the resulting error in the scattering cross-section as a function of depth is nearly parabolic. This has given rise to a compensation scheme which, although not very rigorous, has been used with some success. It is assumed that the sealant, corrosion product and any other layered constituent has the same scattering properties as aluminum apart from a multiplicative factor. In such a case, the uncorrected data as a function of depth can be transformed into equivalent depth in reference material, ζ. The parabolic correction can then be applied. Of course, ζ, cannot be known exactly because the only known absorbtion information is the approximation contained in Eq. (2). The reference coordinate, ζ, is approximated by the relation,

$$\exp(-\zeta_n^{\frac{1}{p}}) = \prod_{(i)}^{n-1} (1-\gamma\sigma_i) \tag{4}$$

for the n-th data point. The parameter p is approximately 1.5. The resulting correction takes the form,

$$\sigma_{n,corrected} = \sigma_n\left(1-\frac{k}{\zeta_{max}^2}(\zeta_n-\zeta_{max})\zeta_n\right) \tag{5}$$

where ζ_{max} is the value of ζ_n for the largest value of n and k is a constant often near unity.
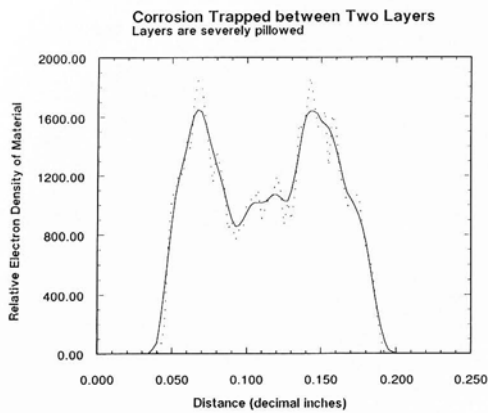
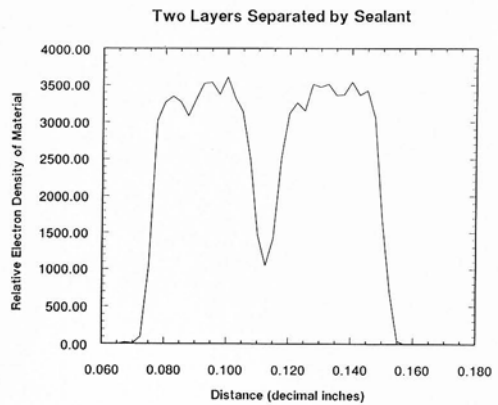Fig. 2. Severely corroded aluminum joint.

Fig 3. Aluminum joint with sealant.

Table 2. Comparison of X-Ray and Micrometer Measurements

	X-Ray Measurement, in.	Micrometer Measurement, in.
Figure 2 Layer 1, metal	0.044	0.043
" " Layer 2, corrosion"	0.041	?
" " Layer 3, metal	0.049	0.048
Figure 3 Layer 1, metal	0.035	0.036
" " Layer 2, sealant	0.007	0.008
" " Layer 3, metal	0.034	0.036

RESULTS

The output pf the system is a plot of the relative electron density, equivalent to the relative scattering cross-section, versus depth into the surface. Figure 2 shows such a plot for two layers of aluminum with a substantial amount of corrosion product trapped in between. By graphically fitting this plot with three boxcars convolved with the aperture function, the thickness of the three layers is obtained. The outer layers are aluminum while the middle layer is corrosion product. Some thickness has been lost from the first layer. The dimensions of these layers as measured and actual are given in Table 2. There is some degradation due to severe pillowing, bulging of the metal, which gives rise to peaking of the boxcars and an apparent degradation of the aperture function as seen by the slope-shouldered appearance of the scan.

Figure 3 shows the same type of result for two flat layers of metal separated by sealant. The sealant in this case is hardly distinguishable from an air gap. Again, fitting boxcars to the two metal layers gives a measurement which is compared with an actual value in Table 2. Because the surfaces are flat and uncorroded, the boxcar shape is easily recognized. This image will be used as an example of the reconstruction steps described above. Figure 4 is the same image without the beam hardening correction which was performed using Eqns. (4) and (5). The reconstruction itself is illustrated by comparing the un-reconstructed image shown in Fig. 4. Figure 3 was obtained from Fig.4 using Eq.(2).

Although the metal in the sample used for Fig. 3 is flat, it has some surface roughness. Figure 6 is an un-reconstructed scan into the surface of a polished piece of aluminum jig plate having negligable roughness. The edge sharpness seen in this scan is slightly greater than that seen in Fig. 3 and much greater than that seen in Fig. 2. Comparison of the edge sharpness in a given scan with that for an ideal surface, ie. Fig. 6, gives information about the roughness and flatness of the surface in question. Figure 7 shows a modulation transfer function curve for the system as obtained from Figure 6.

CONCLUSION

Compton x-ray backscatter has been shown to be a useable method for measuring the thickness of metal layers and for distinguishing corrosion in aluminum. Accuracies of 0.001" have been obtained in most cases and improvement is certainly possible. When Compton backscatter is used for this purpose, the scattering zone, defined by the camera geometry, is scanned through the material. The resulting raw data, counts per volume element at the various positions, requires reconstruction to obtain the actual electron density versus distance. It is from this electron density plot that thickness measurements
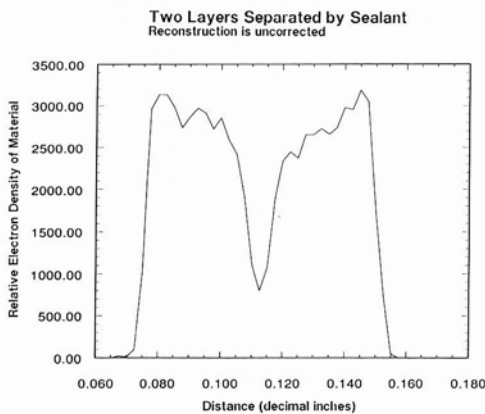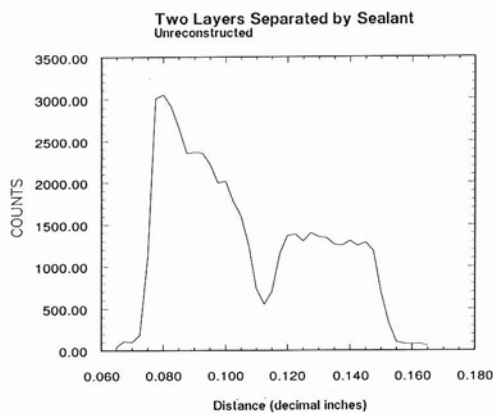
Fig 4. Uncorrected reconstruction
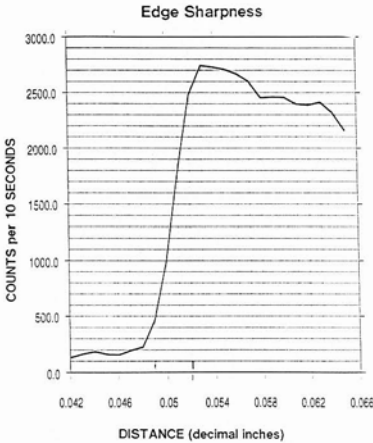
Fig. 5. Unreconstructed data.
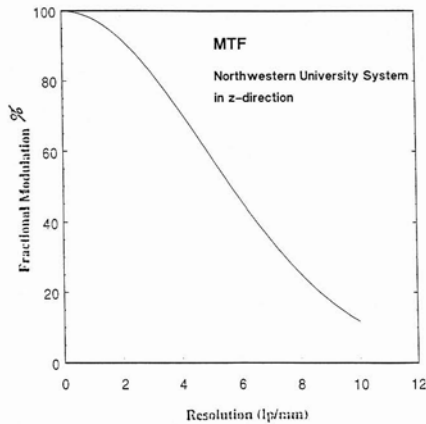
Fig. 6.   Polished surface

Fig. 7. Spatial frequency response

can be made. The reconstruction method used here is in two parts, an approximate reconstruction assuming a constant ratio of electron density to linear x-ray absorbtion coefficient followed by a correction for beam hardening effects.

ACKNOWLEDGEMENTS

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