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ALGORITHM FOR BETTER X-RADIOGRAPHY ANALYSES

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ABSTRACT

A long-standing problem in the characterization of multi-layered ICF capsules is the determination of the position of surfaces and interfaces from x-radiographic images. The accepted procedure for analyzing such images is to calculate the radial second derivative of x-ray absorption through a shell to locate the points of inflection in the absorption vs. radius plot which denote the layer interfaces. The computer routine developed in 1994 as an addition to NIH Image to perform this analysis was subject to unnecessary noise caused by calculating the radial finite second derivative ($\Delta^2 z/\Delta r^2$) from the interpolated radial points. Our most recent algorithm update solves this problem by directly determining the radial infinitesimal second derivative (d^2z/dr^2) of a cubic interpolation of surrounding pixels. This new procedure allows us to make reliable measurements of wall thickness vs. angle and layer uniformity, an improvement over the original method which only yielded layer thickness values averaged over all 360° of the shell.

I. INTRODUCTION

Since x-rays are absorbed but not significantly deflected by material they pass through, x-raying an ICF target can accurately reveal information about its interior structure. A plot of x-ray absorption vs. radius for a target whose layers have different absorption coefficients will be characterized by sharp discontinuities in slope at the layer interfaces (Fig. 1). In the radial second derivative of such a plot, one can accurately identify layer interface positions as strong peaks.

Until recently, the method of characterization designed to make use of these radial plots of x-ray absorption delivered an identifiable signal only if a large number of radial plots were averaged over the entire shell cross section, reducing noise to a managable level. The most current procedure, allows reliable layer interface positions to be determined at individual radii, enabling us to better examine wall uniformity and shell concentricity using x-radiography.

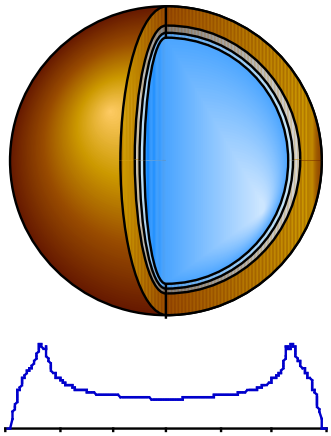


Fig. 1. A shell cross-section and x-ray absorption profile through the corresponding diameter.

II. BACKGROUND

The x-radiography characterization procedure involves digitizing a shell x-ray microscope image and running a computer analysis on it. Our x-radiography images are digitized with a resolution of ~0.86 pixels/μm. The information stored in each pixel of an image is the averaged intensity over a ~1.15 (=1/0.86) μm square area. Usual wall thicknesses are ~3 μm or greater, so this resolution is large enough to capture the signal we want, and higher frequency fluctuations, such as film graininess and x-ray blurring, are averaged away in digitization. Applying a smoothing algorithm between pixels is a valid way to represent the information averaged away in digitization, minus the higher frequency noise. Assuming that the x-ray absorption around a given pixel follows some function $f(x,y)$, an approximation of that function would be given by the two dimensional Taylor series expansion:

$$f(x,y) = f(x_0,y_0) + \frac{df}{dx}(x-x_0) + \frac{df}{dy}(y-y_0) + \frac{\left(\frac{d^2f}{dx^2}(x-x_0)^2 + 2\frac{d^2f}{dxy}(x-x_0)(y-y_0) + \frac{d^2f}{dy^2}(y-y_0)^2\right)}{2} + \frac{\left(\frac{d^3f}{dx^3}(x-x_0)^3 + 3\frac{d^3f}{dx^2y}(x-x_0)^2(y-y_0) + 3\frac{d^3f}{dxy^2}(x-x_0)(y-y_0)^2 + \frac{d^3f}{dy^3}(y-y_0)^3\right)}{6} + \ldots \quad (1)$$

In 1994, General Atomics developed an algorithm to calculate the value of Eq. (1) at any point (ZQuad).[1] In essence, ZQuad performs the desired smoothing in that it assumes a smooth surface exists between pixels, and returns values as necessary to extract absorption vs. radius plots from a shell image. Figure 2 demonstrates the smoothing that ZQuad performs by showing the Taylor series surface fit to a 24×24 pixel area of a shell image.

II. THE OLD METHOD

ZQuad calculates first, second, and third finite derivatives from pixels surrounding (x, y) (Fig. 3). It returns the value calculated by plugging these values into Eq. (1). Calling ZQuad for points from r=200 μm to r=290 μm, evenly spaced every 0.2 μm along a single radial line of a shell image, produces a single plot of x-ray absorption vs. radius over the interesting area of the shell wall (the area containing the layer interfaces). The second derivative of this radial line can then be found finitely (by difference using the calculated intensity points). To obtain meaningful data from the radial second derivatives, the surface fit by ZQuad must be at least cubic; using the first four terms of the Taylor series expansion (the 0th, 1st, 2nd, and 3rd derivative terms) yields a cubic surface.

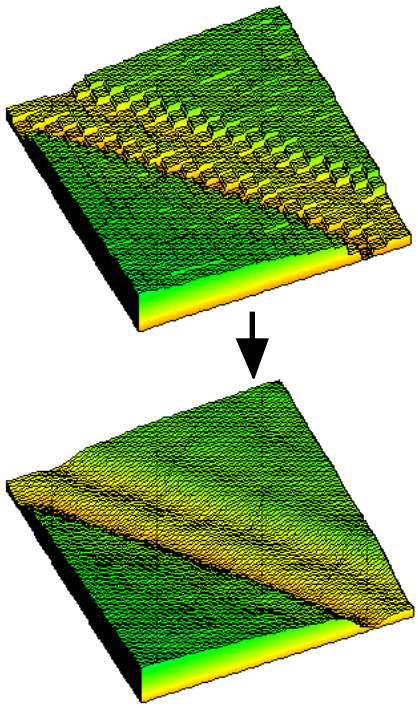
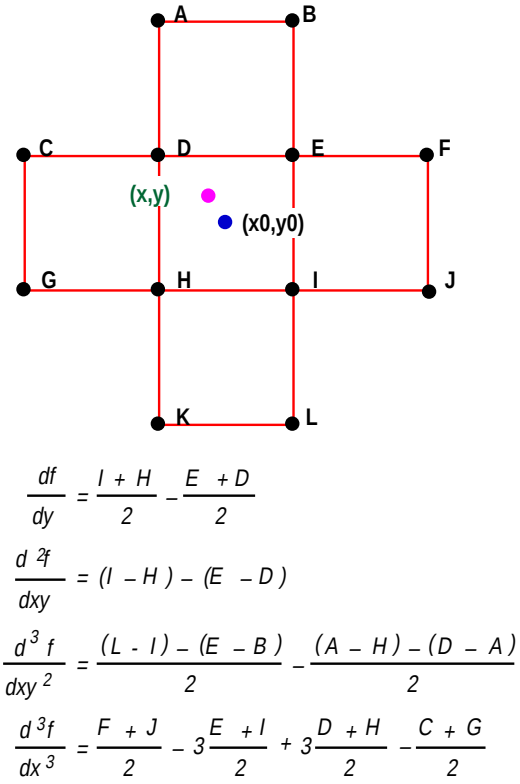


Fig. 2. The smoothing performed by ZQuad. The heights in the top square shows the initial pixel values; the lower square shows the smooth surface generated by the ZQuad interpolation.



$$\frac{df}{dy} = \frac{I+H}{2} - \frac{E+D}{2}$$

$$\frac{d^2f}{dxy} = (I-H) - (E-D)$$

$$\frac{d^3f}{dxy^2} = \frac{(L-I)-(E-B)}{2} - \frac{(A-H)-(D-A)}{2}$$

$$\frac{d^3f}{dx^3} = \frac{F+J}{2} - 3\frac{E+I}{2} + 3\frac{D+H}{2} - \frac{C+G}{2}$$

Fig. 3. For a point at (x,y), one calculates the local finite derivatives from the values, A-F, of the surrounding pixels, as shown above. These are inserted into Eq. (1) to calculate the value at (x,y).

Figure 4 shows a small portion of a single radial line produced by the old ZQuad, and its finite second

derivative. Since each point's value is calculated using the pixels nearest to that point, the radial line plot is characterized by smooth sequences of points calculated using the same set of pixels, with small jumps at pixel edges. Taking the second derivative finitely yields the desired information along the smooth regions, but produces huge spikes at the pixel edges. Figure 5 shows how the spikes displayed in Fig. 4 obscure layer thickness information at a single angle. Wall thicknesses can only be calculated by averaging a large number of absorption profiles over the entire shell image, so one takes the 360° average to get reliable interface locations (Fig. 6).

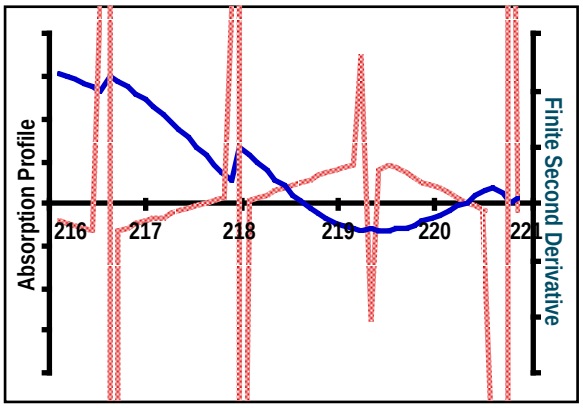


Fig. 4. Absorption as a function of radius (over 4 pixels), and its finite second derivative. The spikes in the second derivative extend to ten times the height of the graph.

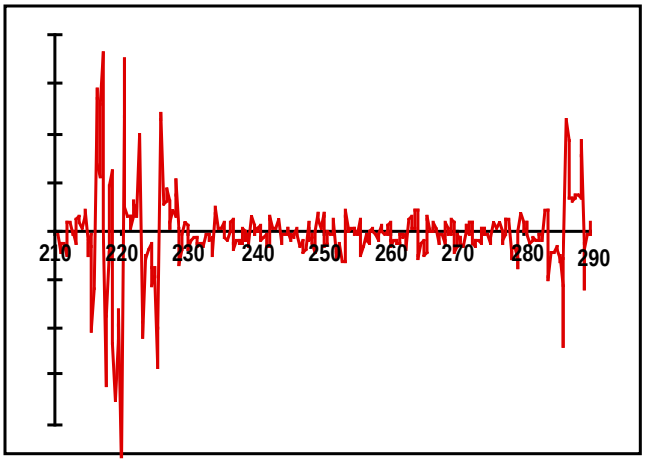


Fig. 5. The finite second derivative of a single radial line calculated by the old ZQuad. Layer interfaces are not identifiable because of the interpixel spikes shown in Fig. 4.

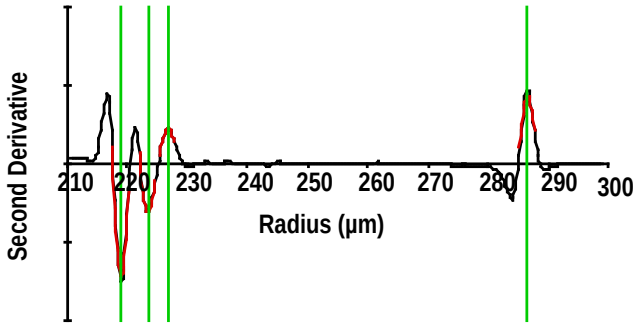


Fig. 6. Average of finite second derivative radial lines around entire shell, using old ZQuad. Using the old ZQuad, only these average wall thickness measurements were available.

IV. THE NEW METHOD

Instead of approximating absorption values and taking the finite radial second derivative, the new ZQuad routine uses the finite local derivatives, calculated in the same manner as the old ZQuad, to directly calculate the infinitesimal radial second derivative of the Taylor series expansion,

$$\begin{aligned}\frac{d^2 f}{dr^2}(x,y) = {} & \frac{d^2 f}{dx^2}(\cos\theta)^2 + 2\frac{d^2 f}{dxy}(\cos\theta)(\sin\theta) + \frac{d^2 f}{dy^2}(\sin\theta)^2 + \frac{d^3 f}{dx^3}(x-x_0)(\cos\theta)^2 \\ & + \frac{d^3 f}{dx^2 y}(y-y_0)(\cos\theta)^2 + 2\frac{d^3 f}{dx^2 y}(x-x_0)(\cos\theta)(\sin\theta) + 2\frac{d^3 f}{dxy^2}(y-y_0)(\cos\theta)(\sin\theta) \\ & + \frac{d^3 f}{dxy^2}(x-x_0)(\sin\theta)^2 + \frac{d^3 f}{dy^3}(y-y_0)(\sin\theta)^2 \\ & + \ldots \end{aligned} \qquad (2)$$

where θ is the polar coordinate corresponding to the x, y coordinates. Having ZQuad calculate and return this value directly completely eliminates the systematic noise of the older method; that is, the jumps in the absorption vs. radius plot due to pixel edges translate into small jumps in the radial second derivative rather than huge spikes. Figure 7 shows the data collected at a single radial line by the new ZQuad, using the infinitesimal second derivative, overlaid on the finite second derivative calculated from the data collected by the old ZQuad. The signal is the same, but the noise is almost gone. Figure 8 demonstrates how the elimination of this noise allows us to make reliable wall thickness measurements at a single angle.

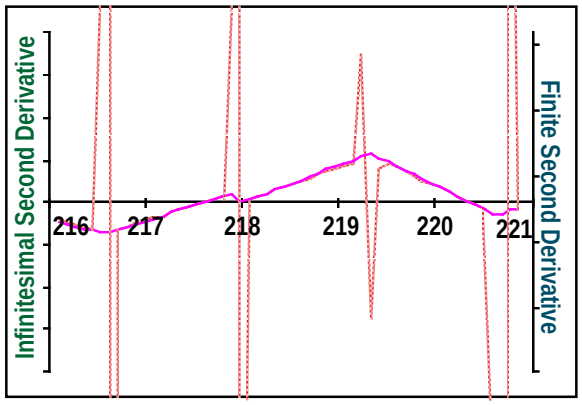


Fig. 7. Comparison of finite (old) vs. infinitesimal (new) second derivative for the same data shown in Fig 4. The new second derivative has no spikes.

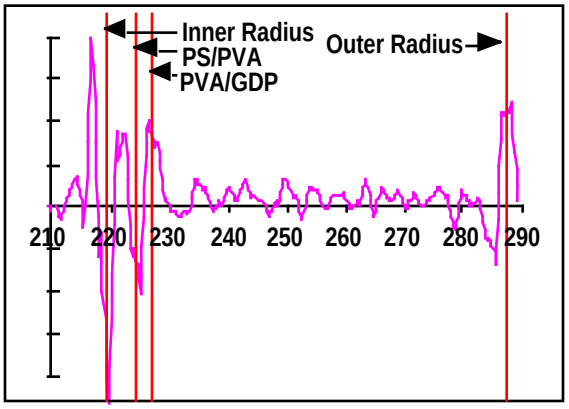


Fig. 8. A single second derivative radial line, calculated by the new ZQuad. Layer interfaces are identifiable.

V. RESULTS

The radial profile images produced by our modified version of NIH Image have always been a qualitative description of shell layers. For instance, one can see in the second derivative radial profile (Fig. 9) that there is a bulge in the PVA layer at ~170°. But, since each vertical line of the radial profile image is the average of only 30 adjacent single radial lines, and since adjacent radial lines at and near 0°, 90°, 180°, and 270° commonly use the same sets of pixels to calculate the same radii, those angles on the old radial profiles were often characterized by low signal-to-noise ratios caused by the fact that the systematic noise from the finite second derivative didn't average out well at those angles. The new algorithm, using the infinitesimal second derivative, eliminates that noise and allows us to locate layer interfaces accurately at different places all around the shell circumferance.

Using the old method, shell defects at 0°, 90°, 180°, and 270°, where the systematic noise wasn't averaged away as it should have been at other angles, would not be visible–only average wall thickness and out-of-roundness information could be obtained. The plot of the new method's output at a single radial line shows us clear, sharp peaks for layer interfaces, allowing us to characterize layer thicknesses as function of angle using x-radiography.

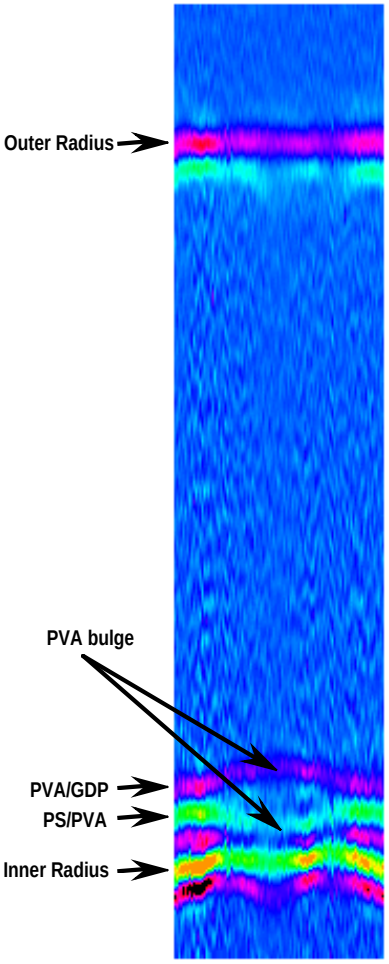


Fig. 9. Radial profile produced by new ZQuad. Due to the quality of the image, as produced by the new ZQuad algorithm, we can confidently measure the PVA layer to bulge from 2.4 μm at 45° to 5.4 μm at 170°.

ACKNOWLEDGMENT

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REFERENCE

1. R.B. Stephens, *J. Vac. Sci. Technol.* **A 13** 979-982 (1995).