QUANTITATIVE COMPUTERIZED LAMINOGRAPHY

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INTRODUCTION

Industrial computerized-tomography (CT) systems have been used to perform visual and quantitative analysis on industrial objects for several years. A tomogram is formed by placing an object between a radiation source and an arc of detectors, and rotating and translating the object to acquire many thousands of measurements through the desired cross-sectional plane. This process takes from 20 seconds to an hour, depending on the size of the object and the quality of image desired; a few minutes is typical. A complete series of closely-spaced cross-sectional tomograms can provide a complete three-dimensional map of the object, but is time-consuming and therefore often not cost-effective.

CT systems can also produce digital radiograms by moving the radiation source and detector array up and down without rotation. While such images, like all radiograms, contain all overlapping features in the object, it is sometimes possible to extract the desired visual or quantitative information needed from a single or few radiograms.

Digital laminography, which is similar to the "focal-plane tomography" used with X-ray film, is a process intermediate between 3-D tomography and radiography in both data-acquisition time and information provided. A digital laminogram uses radiographic data which can be filtered or convolved before laminographic processing. A sequence of radiograms are taken with the object rotated several degrees between each complete radiogram. The image-formation program computes a coarse vertical tomogram on a user-specified surface from this data. Because each radiogram contains projected data of the overlapping layers in the object, the resultant laminogram does not completely remove off-surface features. All the features which are on the user-specified surface stay in focus in the laminogram, while all other features are blurred according to their distance from the surface. It is this process that causes digital laminograms to be intermediate between tomograms, which contain only the information in the scan plane, and radiograms, which contain information equally throughout the object.

APPLICATIONS

Laminography can be a cost-effective method of inspection of industrial objects in several instances. Total inspection of objects is a particularly effective approach for laminography, since 10 to 20 radiograms make up the entire data set needed to form as many user-specified laminograms desired. Thus, laminographic inspection can take a few percent of the time required for total inspection using 3-D tomography. Another laminographic application is the case of objects in which there are one or more high-mass planes in the object; a tomogram using a particular radiation source may not get sufficient penetration in that plane to construct an artifact-free tomogram. By turning the object vertically and taking 10 to 20 radiograms perpendicular to the high-mass planes, a laminogram can be formed that in some instances is of better quality than the high-mass streaked tomogram. Other objects that contain several closely-spaced parallel planes, such as circuit boards, have been found difficult to inspect with tomography, which is difficult to line up on a plane of interest, or with radiography, in which the overlapping layers confound the plane-of-interest, but have been inspected successfully with computerized laminography.

SETUP

The number of radiograms required to achieve acceptable laminographic results depends on the quality desired and the spacing of the features to be distinguished. The choppy effect of the limited angle back-projection algorithm is reduced if the radiograms are at equally spaced angles around the object, with a change in angle of 10 degrees or less. A larger range of angles is necessary if the planes to be distinguished are closely-spaced, as in a circuit board. The laminographic results discussed here were performed with 13 radiograms ranging from -55 to 55 degrees at 10 degree intervals, plus one at 0 degrees, with the exception of the copper/steel phantom which used 10 unevenly spaced radiograms ranging from -55 to 55 degrees.

In order to define the laminographic surface to be constructed, it is often advantageous to take two tomograms as well, at the top and bottom of the object or portion of the object to be laminographically constructed. This allows the user to position lines or arcs in the tomographic sections either visually or with existing edge-fitting techniques, to define the laminographic surface. The user-defined surface need not be a plane. An "unfolded" cylindrical surface can be formed by placing or fitting arcs to the cross-sections of the object in the tomograms. An "unfolded" helical surface can be defined by placing or fitting two lines of differing angles in the tomograms. Another complex surface can be defined by placing or fitting a line in one tomogram and an arc in another; in this case, the surface gradually changes in curvature from the line to the arc.

All results presented were obtained from data collected on an SMS model 101B scanner using a 155 Kv/4.1 Ma X-ray source, with 0.0045 inch vertical and horizontal spacing, detector aperture size of 0.017 X 0.017 inch, and exposure time of 0.1 seconds. All image processing was performed with standard SMS software.

VISUAL LAMINOGRAPHIC RESULTS

A nickel was used to provide an example of visual inspection using laminography. A nickel is approximately 0.012 inches thick, and the features and lettering on the head of a nickel range in height from approximately 0.005 to 0.012 inches; on the tail they range from approximately 0.002 to 0.009 inches. Figure 1 shows 12 of the 13 radiograms used to form the data set. Figures 2 and 3 show the resultant laminograms through the head and tail of the nickel. These laminograms required 10 minutes each to construct using the existing image-formation procedure. Notice the excellent sensitivity laminography affords this object.

A four layer digital circuit board was also used for visual laminographic inspection. The portion of the board inspected was 2.5 inches wide by 1 inch high. The first layer, on the component side, consisted of solder micro-plated leads. The second layer, approximately 0.020 inches away from the first, consisted of leads with no solder. The third layer, approximately 0.010 inches away from the second, was a grounding plane with no solder. The fourth layer, approximately 0.030 inches away from the third, consisted of leads which were wave-soldered. This board, component side up, is shown in Figure 4.

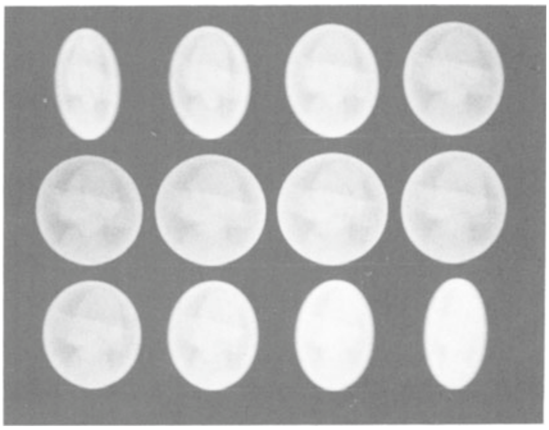

Fig. 1. 12 of 13 digital radiograms of the nickel used as the laminographic data set, each taken in 8 minutes.

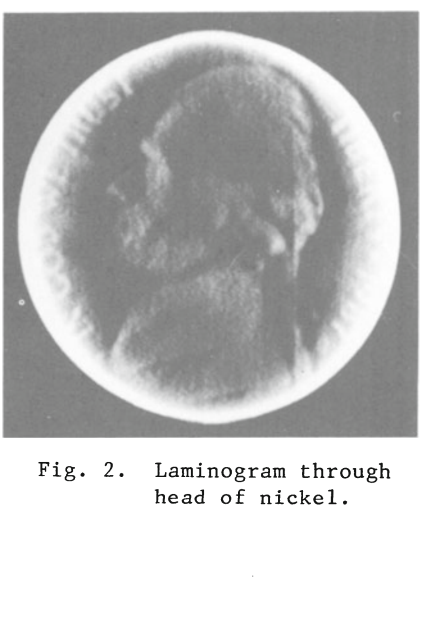

Fig. 2. Laminogram through head of nickel.

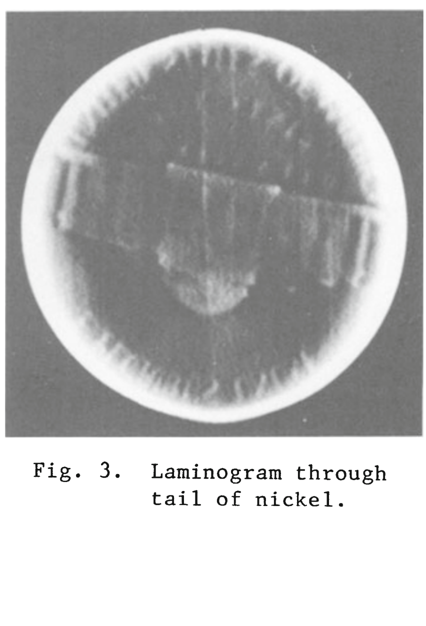

Fig. 3. Laminogram through tail of nickel.

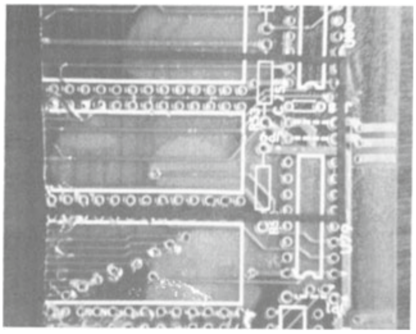

Fig. 4. Four layer circuit board used, component side up. Inspection area indicated.

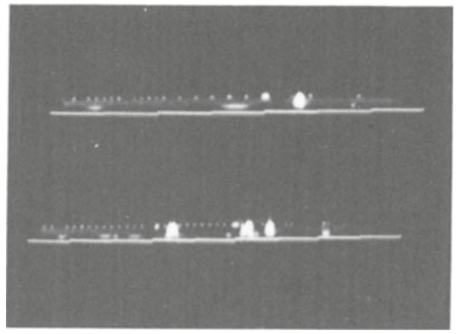

Fig. 5. Two tomograms, top and bottom, with fitted lines defining helical laminographic surface.

Two tomograms were taken for the laminographic plane positioning. Lines were fit to the component side in each to determine the laminographic surface. In this case, the board had a slight twist to it, which resulted in a 1.5 degree difference in angle of the two fitted lines. The resultant laminograms were therefore not planar, but actually unfolded helical surfaces. Figure 5 shows these tomograms and the fitted lines.

The laminograms of the four planes are shown in Figures 6 and 7. The first plane (Figure 6, top) shows the horizontal wires quite well. The second plane (Figure 6, bottom) shows the vertical wires in that plane, but also clearly depicts the horizontal wires of plane 1. This is due to the close spacing between these planes (0.020 inches), and the fact that the wires in plane 1 are soldered and therefore more dense than the plane 2 wires. The third plane (Figure 7, top) shows the grounding plane to the left, but also shows the wires from planes 1 and 2, also due to the close spacing (0.010 inch between planes 2 and 3) and the higher density of wires in plane 1. Plane 4 (Figure 7, bottom) shows in excellent detail the wires in the plane, with little blurring effect. This is due to the larger spacing (0.030 inch between planes 3 and 4), and the large amount of solder deposited on the wires from the wave-soldering process.

QUANTITATIVE LAMINOGRAPHIC RESULTS

To determine the sensitivity of laminography for dimensional measurement, porosity analysis, and flaw detection sensitivity, a 3 by 4 inch copper/steel phantom was constructed which consisted of a 0.125 inch thick copper plate attached to an obscuring steel plate varying in thickness from 0.060 to 0.120 inches. The copper plate had various holes and features drilled in it, including four series of holes with respective diameters of 0.010, 0.020, 0.040 and 0.100 inches, each with respective spacing of 0.050, 0.070, 0.100, and 0.200 inches. The phantom is pictured in Figure 8, and a radiogram of the phantom is shown in Figure 9.

There is a noticeable mass over-shoot/under-shoot effect in the laminogram, shown in Figure 10. The radiographic data was convolved before processing into a laminographic plane; because of the limited-angle back-projection algorithm, edges in the laminogram tend to be overestimated in density on the metal side of the edge, and underestimated on the air side. This effect also occurs in a limited-angle tomogram. This poses a new problem in obtaining accurate dimensional results from the laminogram.

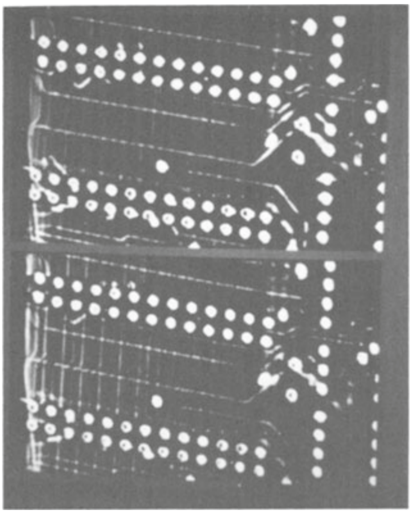

Fig. 6. Laminograms through plane 1, top, and plane 2, bottom.

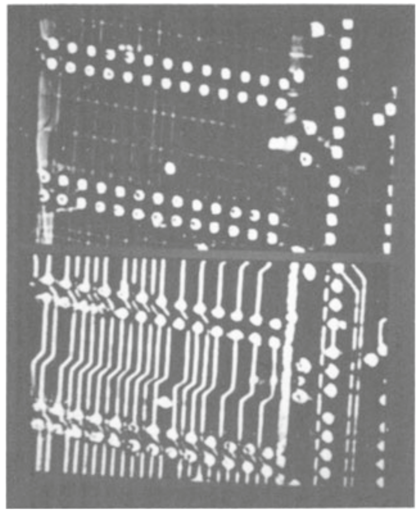

Fig. 7. Laminograms through plane 3, top, and plane 4, bottom.

Fig. 8. Top: Copper portion of copper/steel phantom. Bottom: Steel plate of copper/steel phantom.

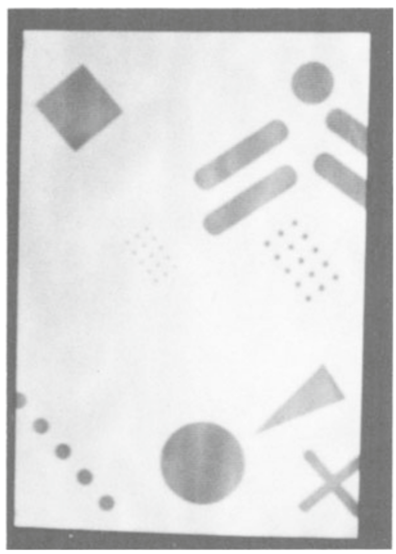

Fig. 9. Radiogram of copper/steel phantom at 0 degrees, taken in 25 minutes.

Three methods are currently being used to obtain dimensional measurements in tomographic and radiographic data. The methods differ in the definition of the edge in a density-map-type image, of which tomograms, radiograms, and laminograms are grouped. The global-edge-threshold method is used primarily on artifact-free tomograms. In this method, the density value at which the edge occurs is defined as some fraction (usually one half) of the sum of the values of typical air density and

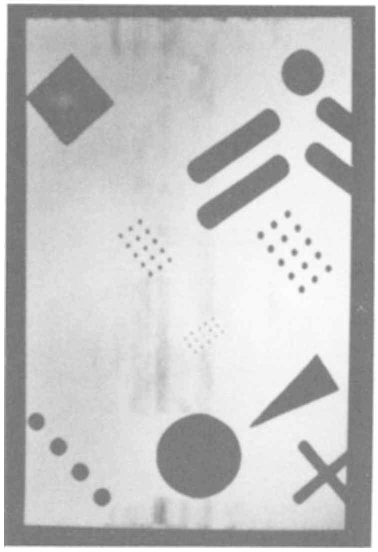

Fig. 10. Laminogram of copper/steel phantom; processing time was 10 minutes.

typical material density in the entire image. The local-edge-threshold method is used primarily on artifacted tomograms, where the high mass objects causing the low penetration are not to be included in the dimensional measurements. In this method, the density value at which the edge occurs is also defined as some fraction of the sum of the values of typical air density and typical material density, but only in the portion of the image to be measured. The dynamic-edge-threshold method was developed to perform measurement analysis on radiograms. In this method, no one density value is used as the value at which the edge occurs, since underlying and overlying features projected in the radiogram cause the density values to vary. The density value at which the edge occurs is found at each point through an iterative method which analyzes the shape of the density curve at each position.

Tables 1 and 2 show the spacing and diameter measurement results using each of the three measurement techniques, for each of the four series of holes as well as the single 0.25 and 0.50 inch diameter holes in the object. No dynamic-edge-threshold measurement was possible on the 0.010 inch diameter holes due to the lack of density curve resolution on the small diameter. In general, the results of measurement analysis on the 0.010 inch diameter/0.050 inch spacing holes were not as precise as the larger holes. Although these holes can be clearly distinguished, the size and shape of the holes were imprecise due to resolution limitations. However, these holes were useful in examining porosity and flaw analysis accuracy. The central 0.010 inch diameter hole is blocked with a broken drill bit; the added mass in the hole can be seen visually and examined through density analysis of the area.

The spacing results for each of the holes, shown in Table 1, show biases of less than 0.001 inch in all cases. This is to be expected, since the position of the center of the hole is very stable regardless of the method used to extract the edge position. The standard deviations of the spacings are around 0.001 inch with the exception of the 0.050 inch spacing holes. This 0.001 inch consistency of the spacing is equivalent to that historically obtained in measurement analysis of tomograms.

Table 1. Measurement analysis results of the spacing of holes in the copper/steel laminographic phantom.

	Global-Edge-Threshold	Local-Edge-Threshold	Dynamic-Edge-Threshold
0.050" Spacing:			
AVERAGE	0.0499	0.0507	------
BIAS	-0.0001	+0.0007	------
STD	0.0032	0.0033	------
0.070" Spacing:			
AVERAGE	0.0702	0.0704	0.0703
BIAS	+0.0002	+0.0004	+0.0003
STD	0.0013	0.0013	0.0012
0.100" Spacing:			
AVERAGE	0.1002	0.1001	0.1001
BIAS	+0.0002	+0.0001	+0.0001
STD	0.0006	0.0005	0.0006
0.200" Spacing:			
AVERAGE	0.1996	0.1993	0.1996
BIAS	-0.0004	-0.0007	-0.0004
STD	0.0008	0.0010	0.0006

The diameter results for each of the holes, shown in Table 2, show several different trends. The standard deviations are smaller in the dynamic edge threshold method, since the shape of the density curve, and hence the shape of the edge, is more closely followed than in the constant edge threshold methods. With all methods, however, the standard deviations are around 0.001 inch with the exception of the 0.010 inch diameter holes. This consistency once again approaches the consistency obtained from tomographic analysis. The large biases found are the result of the over-shoot/under-shoot effect previously discussed. Using the global edge threshold method, these biases tend to decrease as the size of the holes increase. Using the other two methods, the trends are not as uniform due to the manner in which the over-shoot/under-shoot effect is affecting the surrounding data.

FUTURE WORK

Analysis techniques for tomographic and radiographic inspection have been investigated for several years, and measurement methods have been developed to provide accurate dimensional results based on these types of images. As the research into laminographic inspection continues, quantitative laminographic results can be improved as more sophisticated analysis techniques are developed which address the special considerations of laminographic data. Analysis techniques which specifically address the over-shoot/under-shoot effect in the laminographic data would significantly decrease the biases found in the measurement results of the copper/steel phantom, for instance. With these techniques, it is expected that dimensional accuracies for laminographic data will approach the existing accuracies found with tomographic analysis.

Visual laminographic results can be improved by investigating and implementing different weighting functions by which to combine the radiographic data in the back-projection algorithm. At present, each radiogram is combined with equal weight to produce the laminogram.

Table 2. Measurement analysis results of the diameters of holes in the copper/steel laminographic phantom.

	Global-Edge-Threshold	Local-Edge-Threshold	Dynamic-Edge-Threshold
0.010" Diameter Holes:			
AVERAGE	0.0161	0.0166	------
BIAS	+0.0061	+0.0066	------
STD	0.0021	0.0028	------
AVE RMS EXCURSION	0.0037	0.0037	------
0.020" Diameter Holes:			
AVERAGE	0.0245	0.0186	0.0252
BIAS	+0.0045	-0.0014	+0.0052
STD	0.0006	0.0007	0.0003
AVE RMS EXCURSION	0.0014	0.0012	0.0011
0.040" Diameter Holes:			
AVERAGE	0.0441	0.0405	0.0407
BIAS	+0.0041	+0.0005	+0.0007
STD	0.0009	0.0009	0.0005
AVE RMS EXCURSION	0.0013	0.0011	0.0011
0.100" Diameter Holes:			
AVERAGE	0.1008	0.0990	0.1011
BIAS	+0.0008	-0.0010	+0.0011
STD	0.0017	0.0018	0.0006
AVE RMS EXCURSION	0.0014	0.0015	0.0009
Single 0.250" Diameter Hole:			
DIAMETER	0.2500	0.2516	0.2528
BIAS	0.0000	+0.0016	+0.0028
RMS EXCURSION	0.0023	0.0024	0.0009
Single 0.500" Diameter Hole:			
DIAMETER	0.5000	0.5046	0.5042
BIAS	0.0000	+0.0046	+0.0042
RMS EXCURSION	0.0024	0.0027	0.0011

The laminographic image-formation process is currently being adapted to provide a factor of 10 or more speed-up. This will further increase the attractiveness of this non-destructive inspection method.

CONCLUSIONS

Computed laminography has promising prospects for the analysis of objects that have previously been difficult or time-consuming to inspect using digital radiography, computed tomography, or other non-destructive methods. The laminographic results presented indicate that excellent visual and quantitative results can currently be obtained. Computed laminography will provide industry with another powerful and unique non-destructive testing technique.