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ANALYSIS OF X-RAY IMAGE QUALITIES -ACCURACY OF SHAPE AND CLEARNESS OF IMAGE - USING X-RAY DIGITAL TOMOSYNTHESIS

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Abstracts X-ray laminography and DT(digital tomosynthesis) that can form a cross-sectional image of 3-D objects promise to be good solutions for inspecting interior defects of industrial products. The major factors of the digital tomosynthesis that influence on the quality of x-ray cross-sectional images are also discussed. The quality of images acquired from the DT system varies according to image synthesizing methods, the number of images used in image synthesizing, and X-ray projection angles. In this paper, a new image synthesizing method named 'log-root method' is proposed to get clear and accurate cross-sectional images, which can reduce both artifact and blurring generated by materials out of focal plane. To evaluate the quality of cross-sectional images, two evaluating criteria: (1) shape accuracy and (2) clearness in the cross-sectional image are defined. Based on this criteria, a series of simulations were performed, and the results show the superiority of the new synthesizing method over the existing ones such as averaging and minimum method.

Keywords X-ray laminography, cross-sectional image, digital tomosynthesis, image evaluation

1. INTRODUCTION

X-ray is used for inspecting inner defects of industrial products. But, in the case of conventional X-ray radiography images, it is very difficult to recognize the inner shape of the objects correctly, because all the objects on the projection line are overlapped in the image. On the other hand, X-ray cross sectional imaging systems which can form an arbitrary cross-section image of 3D object make it easy to inspect inner shape or structure of that. PCB solder joint inspection is one of the industrial field which need X-ray inspection system. Lately, new electrical packages or technologies are developed and used such as BGA(Ball Grid Array), FCA(Flip Chip Array), J-type lead, multi-layered PCB. But, it is unable to inspect those chips by visual inspection system, because the solder joints are hide under the chips itself. Furthermore it is difficult to inspect by conventional X-ray transmission image for the overlapping problem, so X-ray cross-sectional imaging systems are needed.[1]

An X-ray cross-sectional image is integrated from a lot of images projected from different directions, and there are several method like as tomography, laminography, digital tomo-synthesis. Tomography has been mainly used in medical area, but is applied to industrial field such as precision inspection of casting products.[2]

Laminography is another method for acquiring cross-sectional image, and originated by Bocage[3]. Its principle comes from synchronized motion between the X-ray source and the detector to form a slice image. Laminography is applied to inspect PCB solder joint by Adams[1], Black[4], Rooks[5,6]. The basic principle of digital tomosynthesis is same as that of laminography, but the difference is in integrating images projected from different views by software not by hardware[7].

In this paper, digital tomosynthesis method to lessen the artifact and blurring effect in laminography images will be discussed. As a cross-sectional image is made by synthesizing a number of projected images, the image qualities are varying as the image synthesizing method. In this research, a new image synthesizing method named 'log-root method' is proposed to get clear and accurate cross-sectional images, which can reduce both artifact and blurring generated by materials out of focal plane.

There are three major factors which have effect on the quality of cross-sectional image, and those are 1) image synthesizing method, 2) projection angle, 3) number of images used in the synthesis. And the qualities of the image is defined and evaluated by two criteria : 1) shape accuracy and (2) clearness in the cross-sectional image.

A series of simulations was performed with different conditions of the 3 major factors to the basic objects such as cone, pyramid and hemisphere.

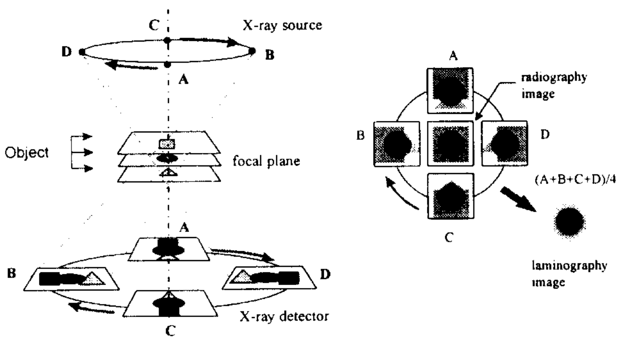
2. PRINCIPLE OF X-RAY CROSS-SECTIONAL IMAGING METHOD

2.1 Laminography

The principle of laminography is enhancing the contrast of an X-ray image for an specific plane.

Figure 1.(a) shows the principle of laminography, a synchronized motion between X-ray source and the detector generates an geometrical focal plane and forms an X-ray slice image of that. Objects in the focal plane are always projected at

the same position of the detector. On the other hand, those that are not in the focal plane are projected to other positions of the detector and thus blurred as the source and detector move in a complete circle. Thus the 'noise' from the material above and below the focal plane is eliminated when all the images on the detectors are overlapped [1].



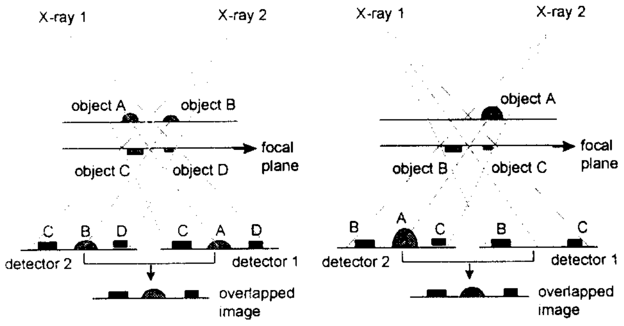
(a) synchronization (b) laminography for circle

Figure 1. The principle of laminography

Figure 1.(b) shows an example of laminography, there are circle, triangle, rectangle object in the focal plane, upper and below the focal plane respectively. The object 'circle' in the focal plane is projected at the same position on the detector, but the other objects in the out of focal plane are projected at shifted positions. Thus by averaging those projected images, the circle is preserved and the triangle and the rectangle are blurred.

2.2 The effect of the material out of focal plane

The objects out of focal plane may be blurred and to be eliminated in the laminography image. But the blurring can make the image unclear, moreover the effect will be big by the material with low X-ray transmit rate. And, the shape in the focal plane can be distorted by the out of focal plane material, which is called 'artifact' [7,8]. Artifact is an radical problem of laminography for its principle that projects all the objects on the focal plane and outside of that as well.



(a) Artifact 1 (b) artifact 2

Figure 2. Artifact

There are two kinds of artifact, the first one is caused by overlapping between materials not in the focal plane, which is defined as artifact 1. And that is closely related to projection angle of system, so it can be overcome or lessened as the projection angle varies. The other one is caused by a 'large object' that is not in the focal plane. Namely, its effect is too big to be removed just by averaging, and defined as 'artifact 2'. Figure 2. (a) and (b) explains graphically artifact 1 and artifact 2 respectively.

2.3 Digital Tomosynthesis

In a laminography image, artifact distorts the shape of the cross-section and blurring effect makes the image unclear but, digital tomosynthesis makes overcome these defects. The basic principle of digital tomosynthesis is almost the same as that of laminography except in the fact that DT synthesize images after saving them in digital memory. The cross-sectional image is formed by various image synthesizing methods such as averaging, minimum with the preserved images at memory. The objects out of focal plane can be seen as a form of blurring or shape distortion in the laminography image, but these can be eliminated or lessened by digital tomosynthesis.

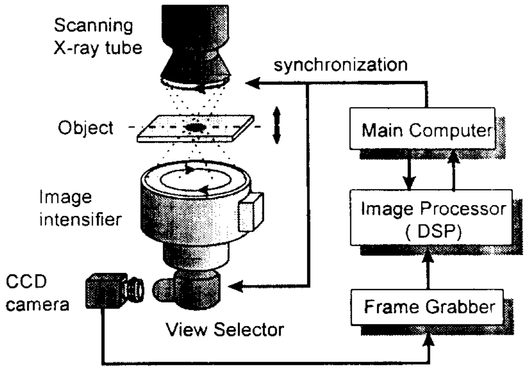


Figure 3. Digital tomosynthesis system

The practical digital tomosynthesis system with an principle of laminography is presented by figure 3. In the system configuration, to project X-ray to an object at different directions electrically scanning X-ray tube is used instead of rotating X-ray tube mechanically. And image intensifier with an large input screen is used as a X-ray detector so as to get all images projected at different directions. By configuring the system as this, we can get X-ray projection image with different directions or various projection angles and magnifications without moving mechanically any part of system.

3. THE MAJOR FACTORS INFLUENCE ON IMAGE QUALIITY AND EVALUATION CRITERIA

Both X-ray radiography image and X-ray cross-sectional image have gray level determined by properties of objects. Especially in cross-sectional images, we can recognize the shape of the cross-section just by the gray level(intensity) in the image, namely, dark area in the image can be regarded as the object in the focal plane. So, for easy recognition or analysis of an X-ray cross-sectional image, the contrast should be high. So, we can evaluate the X-ray cross-sectional image by two criteria; 1)how can we apart the cross-section part easily from the image 2)how accurate is the cross-section part in the image compared to that of object. The 3 major factors that have a effect on the image quality are X-ray projection angle, the number of images used for generating a cross-sectional image, image synthesizing method. In this chapter, the effects of these factors on X-ray cross-sectional image are discussed.

3.1 *X-ray projection angle*

Artifact that makes distortion of cross-section image is one of the limitations of the laminography. And that is very close relations to the X-ray projection angle, because the amount of shift on the detector by out of focal plane material is varies as X-ray projection angle.

3.2 *Number of images used for image synthesizing*

The number of images used for acquiring a cross-sectional image is also important, because the effect of the materials out of focal plane should be blurred and removed by averaging those images. So if the number is not sufficient, those materials can cause a distortion of the cross-section and make the image unclear. Especially, artifact 2 can be reduced much or removed as the number of images increases. However the number of images should be restricted by the limitations of the memory and time for calculating

3.3 *Image synthesizing method*

In digital tomosynthesis, an cross-sectional image is build by synthesizing a series of projected images. And, it is good merit of digital tomosynthesis that various image synthesizing method can overcome the limitations of laminography such as blurring or artifact, and thus advance the quality of images.
The image qualities are different as image synthesizing methods varies. Image synthesizing should be performed to eliminate the effect of non-focal plane material and to advance the contrast of image. For this purpose, an series of operations are carried out between the images and named 'log-root method'. For convenience, all the images used in this paper are 8bit gray scale images. Fig 4. Shows the procedure of 'log-root method' and the points are as follows.

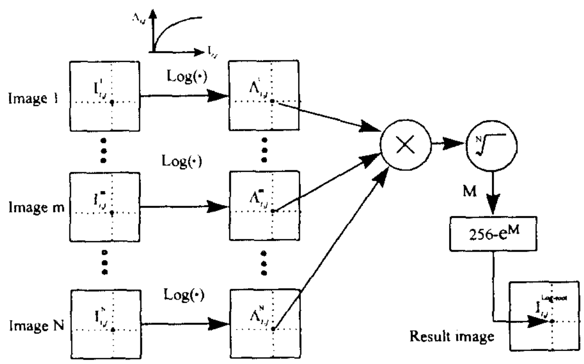


Figure 4. Log-root method

Step 1 : Define a intermediate value Λ with the intensity value I using 'log' operation. This is for granting weight on the low intensity values before integrating them using the nonlinear characteristic of log function.

$$\Lambda^m_{i,j} = ln(256 - I^m_{i,j}) \tag{1}$$

where, $I^m_{i,j}$ is an intensity value of i-th row, j-th column pixel in a m-th image

Step 2 : An integrating value M which is under the root operation after multiplying all the Λ values is acquired, so the value M has a meaning of average of Λ values.

$$M_{i,j} = \sqrt[N]{\Lambda^1_{i,j} \times \Lambda^2_{i,j} \times \cdots \times \Lambda^m_{i,j} \times \cdots \Lambda^{N-1}_{i,j} \times \Lambda^N_{i,j}} \tag{2}$$

Step 3 : M value (has the meaning of value Λ) is converted as an original intensity value again as defined (1).

$$I_{i,j}^{Log-root} = 256 - e^M \tag{3}$$

If any Λ value has '0', namely there is no object on the projection line, the intermediate value $M_{i,j}$ can be '0' and thus the result value is to be $I_{i,j}$=255. So in the synthesized image, there is no object at the i-th row, j-th column. The multiplicity operation is used for eliminating blurring effect after all.

Therefore, an averaged and eliminated blurring effect image can be acquired by 'log-root method', and weighting effect by 'log' transform of intensity may improve the contrast(or clearness) of the image.

3.4 *Image evaluation criteria*

To evaluate cross-sectional X-ray images, we defined two criteria. One is Accuracy of shape which tells how accurate the cross-section is in the image , and the other is clearness of image which tells how easily we can recognize the cross-section part in the image.

The rms errors of the lengths from a mass center to the border for N_p evaluation points represent the shape error, and defined as the equation (4) and figure 5.

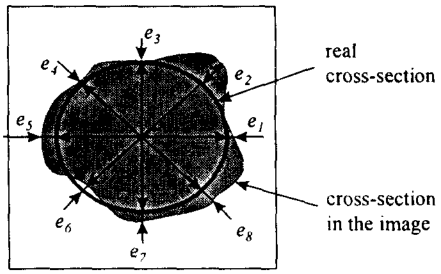


Figure 5. Definition of shape error

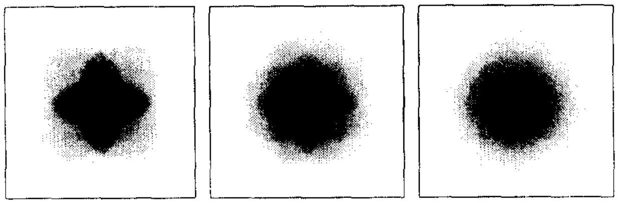
$$E_{rms} = \sqrt{\frac{E_{sum}}{N_p}}, \quad E_{sum} = \sum_i^{N_p} \left(\frac{r_i - r_{o,i}}{r_i}\right)^2 \tag{4}$$

r : the distance from a center to the border in image
r_i : the real distance value from a center to the border
N_p : the number of points used for the evaluation

The error E_{rms} has a value between 0 and 1, and we define a accuracy of shape value as $1-E_{rms}$. So, the shape will be evaluated to be accurate as the value goes to 1.

An cross-sectional image can be clear when the gray values between the part of object and background in the X-ray image are apart from each other. So the intersection area between two regions's intensity distributions can be used as evaluation of the clearness of the image.

At first, the image is divided into the cross-section area and background area, and the mean values and the standard deviations are calculated for each regions. Then, from the values two standard distribution functions, which represent the intensity



(a) 4 images (b) 8 images (c) 16 images

Figure 10. Cross-sectional images : cone, focal plane II

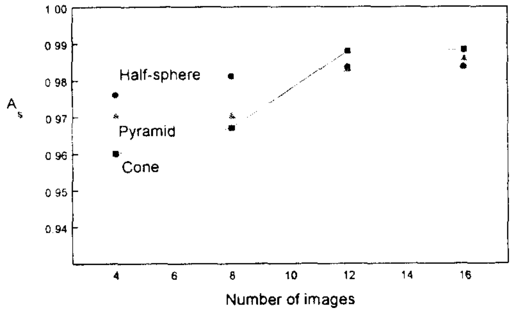
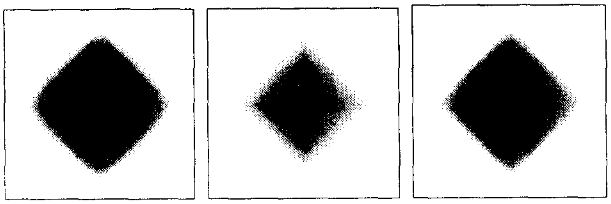


Figure 11. evaluation of images : accuracy of shape with respect to the number of images to be synthesized

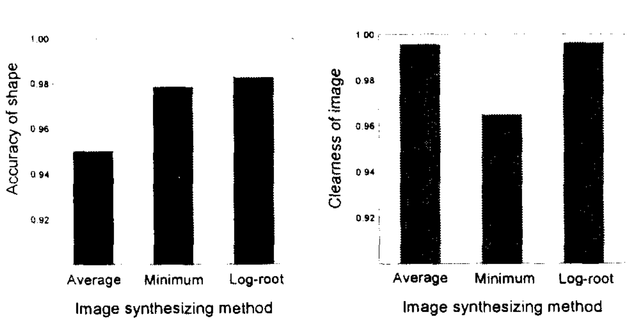
4.3 Image synthesizing method

Figure 12(a),(b),(c) are cross-sectional images for the case of focal plane I of the pyramid by a number of image synthesizing methods. And figure 12(c) shows the effect of 'log-root' method on the image compared with other ones such as average, minimum method. For the case of average method, it is almost the same as laminography image, and thus there exist blurring effect. And for the case of minimum method, the border is some obscure though there is no blurring effect. But in the third image, synthesized by log-root method, has no blurring effect and no obscure region at the border as well.



(a) Average (b) Minimum (c) Log-root

Figure 12. Images from various synthesizing methods



(a) Accuracy of shape (b) Clearness of the image

Figure 13. evaluation of the images in figure 12

Figure 13 shows the merits of the log-root method compared with other ones. Log-root method has a good performance in both the accuracy of shape and the clearness of the image.

5. CONCLUSIONS

In this research, an X-ray digital tomosynthesis system and a new image synthesizing method was proposed, and the effects of 3 major factors on the image quality has been discussed. The 3 major factors are X-ray projection angle, the number of images used in synthesizing and the image synthesizing methods. And to evaluate a cross-sectional images, two evaluation criteria, which are the accuracy of shape and the clearness of the image, have been defined. From the simulations for a number of basic objects, we can see the effect of the major factors on the quality of the image. Generally, the distortion of shape by artifact can be reduced or removed as the projection angle or the number of images increases. Images synthesized by 'log-root' method, which is proposed in this paper, are improved both criteria in the accuracy of shape and the clearness of the image.

ACKNOWLEGEMENT

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distributions, are generated. And, the unclearness of the image U_s is defined as the intersecting area between the two standard distribution functions. (figure 6.)

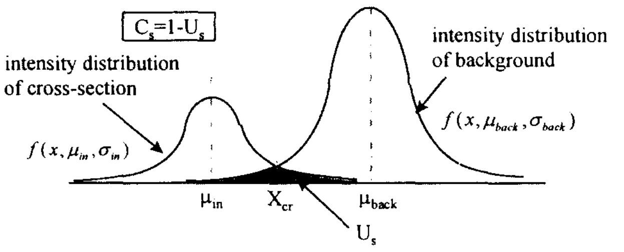


Figure 6. Definition of the clearness of a image

$$f(x,\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/(2\sigma^2)} \quad -\infty < x < \infty \qquad (5)$$

$$U_s = Z_{in}(x > x_{in}) + Z_{back}(x < x_{back}) \qquad (6)$$

where, $x_{in} = \dfrac{X_c - \mu_{in}}{\sigma_{in}}$, $x_{back} = \dfrac{X_c - \mu_{back}}{\sigma_{back}}$

μ_{in} : mean of the intensity distribution in cross-section area

σ_{in} : standard deviation of the intensity distribution in cross-section area

μ_{back} : mean of the intensity distribution in background

σ_{back} : standard deviation of the intensity distribution in background

X_c : the intersection point of two distribution function

The overlapped area C_s between two distribution functions has a meaning of the ambiguity in the border of the cross-section, and has a value within 0 and 1. So, the clearness of the image C_s can be defined as the subtraction of C_s from 1.

$$C_s = 1 - U_s \qquad (7)$$

Clearness of the image C_s has a value from 0 to 1, and we can say the image 'clear' as the value C_s goes to 1.

4. SIMULATIONS

To verify the effects of major factors on the image qualities, a series of simulations by computer was performed to the basic objects. In the simulations, any optical distortion from the image intensifier's input screen or camera lens is not considered.

We can acquire DT images by synthesizing a number of X-ray radiography images which is generated by computer simulation. And the images will be evaluated and discussed by two evaluating criteria defined previously.

Figure 7. shows the objects used in simulations, which are cone, pyramid, hemisphere.

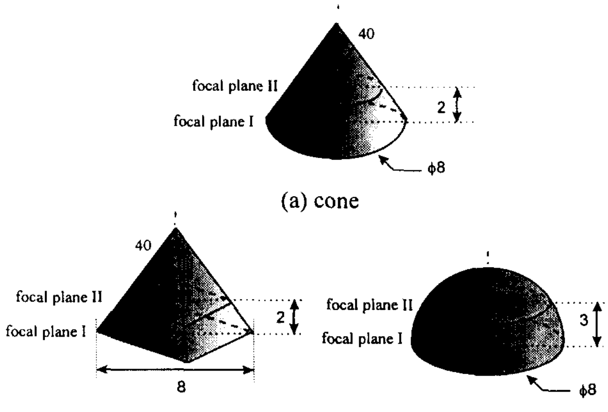
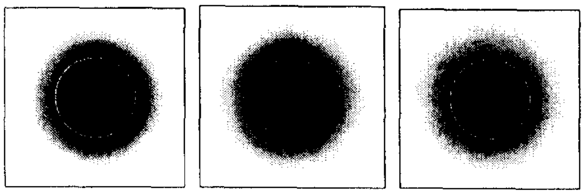


Figure 7. Objects for simulations

4.1 X-ray projection angle

The distortion of cross-sectional shape in laminography is caused mainly by projection angle. And Figure 8 shows an simulation results which are for the focal plane II of the hemisphere; Fig 7(c). From the figure, we can see the effect of projection angle on the shape distortion in the image. In the case of lager angle, the cross-section in the image are more close to the real object of the focal plane (white lines in the images).



(a) angle 25° (b) angel 35° (c) angle 45°

Figure 8. cross-sectional images : hemisphere, focal plane II

Figure 9 shows an evaluation of the images for the accuracy of shape defined chapter 3.4, which includes the cases of the other objects (hemisphere and pyramid) as the X-ray projection angle varies from angle 25° to 45°

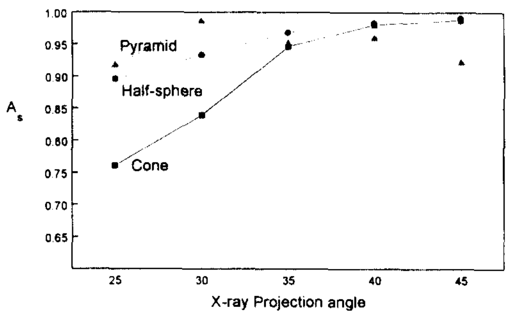


Figure 9. evaluation of images : accuracy of shape

4.2 Number of images used for synthesizing

Figure 10 shows the effect on the cross-section image, and as the number of images increases, the images present the cross-sectional shape of the object more accurately.