X-ray imaging in pin-in-paste technology

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Abstract

Today, pin-in-paste technology is used extensively. With the help of pin-in-paste, through-hole devices can be soldered using a standard surface mount technology (SMT) process and hereby a reduction in wave soldering is possible. This can result in cost savings and a decrease in production cycle time. To ensure successful pin-in-paste soldering the following steps must be taken: solder paste volume calculations for through-hole components; stencil aperture design for the pin-in-paste application; solder paste deposition through stencil printing, application of solder volume increasing techniques after printing; reflow profile optimization; inspections using special methods for each individual process; final tests.

The paste is printed into the through-holes. For high quality pin-in-paste solder joints a sufficient volume of paste is a fundamental requirement. Nevertheless, after printing the through-hole-filling is usually unknown.

In this paper a new method is described how to accurately determine the volume of solder alloy in solder paste that is present in the through-hole, using X-ray measurements, image processing and calculations. In addition, a method is suggested to determine the measuring characteristics and gray-scale linearity of the X-ray machine.

Keywords

X-ray image · pin-in-paste · volume measurement · qualification.

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1 Introduction

In this paper, we describe a method of determining the preliminary qualification of pin-in-paste (PIP) using X-ray images and subsequent evaluation by image processing to calculate the accurate volume of the solder alloy in the through-hole after stencil printing.

In lead-free wave soldering technology, higher temperatures, narrower processing windows and special solder pot constructions can create difficulties for the production of reliable electronic devices. Using the methods we propose could result in cost savings and a decrease in the production cycle time.

Pin-in-paste technology uses the same steps as the SMT. Paste is printed into the through-holes as well as through apertures. At the root of the high quality pin-in-paste solder joint is a sufficient volume of paste. If the volume is more than expected, then the likelihood of bridging increases and solder material losses could be significant. In the opposite case, the quality of the soldered joints will not be adequate sufficient (Fig. 1) and it would not meet the standard: IPC-A-610D.
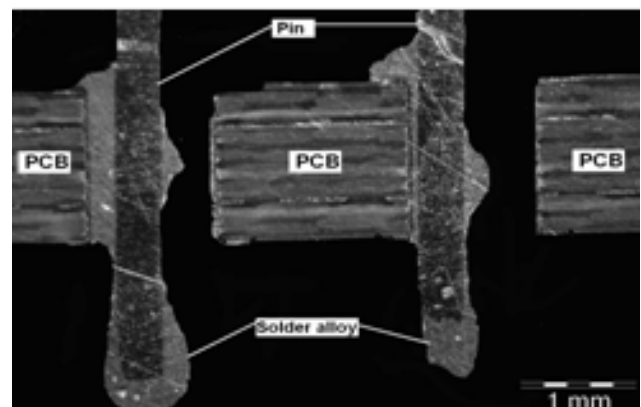

Fig. 1. Cross-section of bad quality PIP joints

Numerous methods are used to produce high quality joints with pin-in-paste technology. Application of overprinting; step stencil; aperture form changing; PIP$^+$ technology (as described in [1, 2]). Hole-filling can also be increased with new family of print heads. Many of these heads are now available, some examples are: DEK Proflow-, MPM Rheometric Pump and Ekra
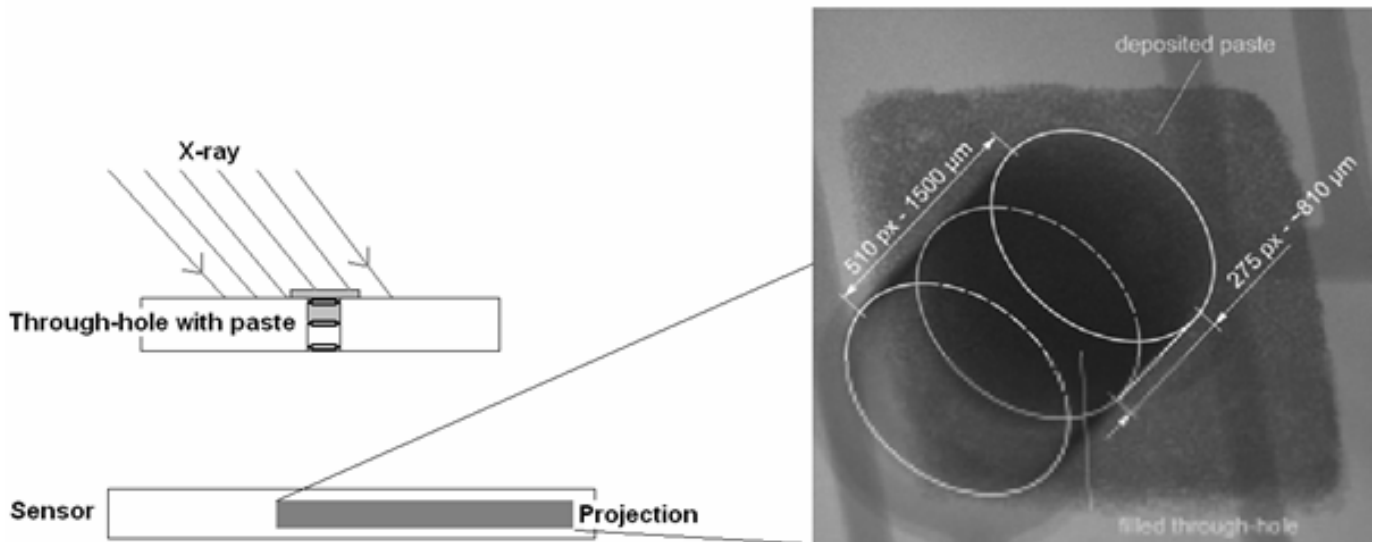
Fig. 2. Fitting of a cylindrical surface on angle view X-ray image

Crossflow.

After stencil printing, the through-hole-filling is unknown although usually it is important to know the paste volume in the through-hole, namely the hole-filling. Standard IPC-7525 and [1, 3] provide a preliminary calculation as to the required volume of paste or solder alloy. As measurement of the solder alloy volume in the through-hole is our aim, measurement accuracy is essential because these volumes are very minute.

In other methods, angled X-ray images are used to measure hole-filling where the manual or mathematical fitting of a cylindrical surface to the paste is more complicated (Fig. 2).

In order to simplify the method and to get more precise shapes orthogonal images are used.

2 Physical background

X-ray inspection machines create gray-scale images. The gray-scales represent the incident and transmitted X-ray intensity ratio which is the function of the thickness and density of the material.

$$I = I_0 \cdot e^{-\mu \rho d} \tag{1}$$

where I_o is the incident intensity,

I is the intensity of transmitted ray,

ρ is density and d is the thickness of the material,

and μ is the mass-absorption coefficient.

In case of solder paste only its metallic content is visible on the X-ray image. The other components, flux and tixotropic materials, are invisible.

3 Measurement characteristics of the X-ray machine

The images used have an 8 bit contrast resolution, giving 256 gray-scales. The measurement characteristics and the linearity (only at the approximate linear part of the characteristics - see Fig. 5) of the X-ray machine are important. They must be measured on the X-ray machine that is used during the PIP qualification.

In our experiments a ceramic test plate was created with accurate laser-cut holes from 50 to 350 μm in depth and paste was deposited onto the plate (Fig. 3).
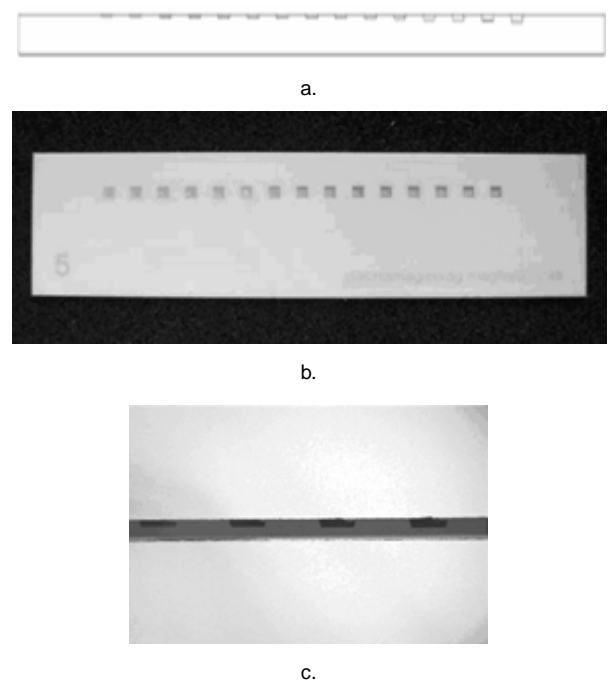

a.

b.

c.

Fig. 3. *a*. Design schematic picture of the ceramic plate 3*b*. The prepared plate *c*. Cross-section of the filled plate

Additionally, holes of 350-1500 μm depth were drilled into a fiberglass-epoxy plate. The darkest gray-scale valued hole was a full pasted through-hole in the plate (Fig. 4).

As described above the measuring characteristics of the X-ray machine (Fig. 5) are available. A curve or to the approximately linear part a line can be fitted on the measurement characteristics. The equation of the curve or line can be used to calculate the "solder alloy thickness" in the hole.

The deposited solder alloy volume can be calculated and measured using the geometrical considerations shown in Fig. 6.
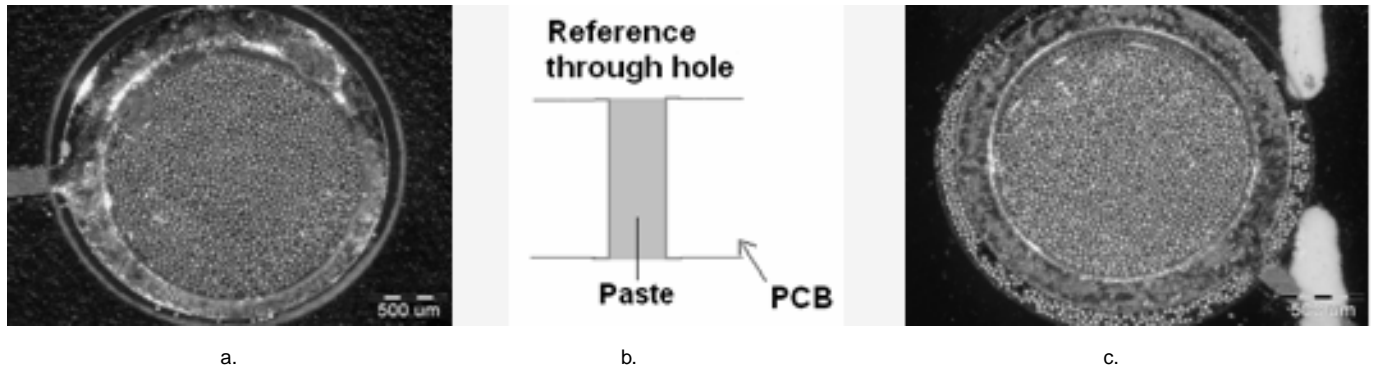
Fig. 4. *a*. The full-filled through-hole shown from above *b*. The schematic picture of the full-filled through-hole *c*. A picture of the full-filled through-hole from underneath
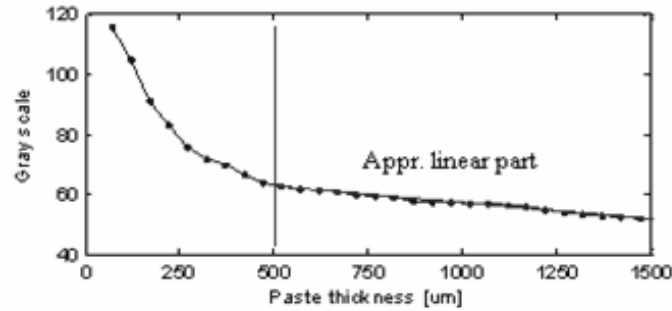

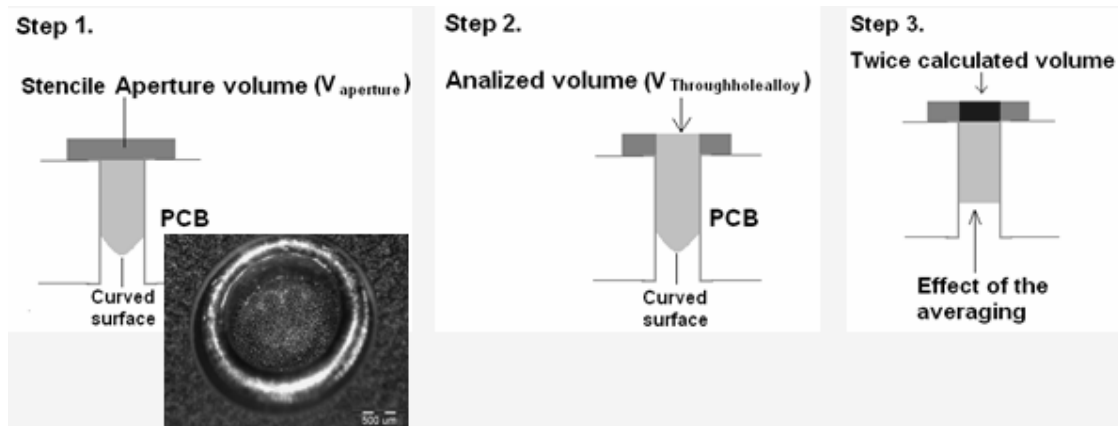**Fig. 5.** Example of X-ray machine characteristic

Fig. 6. Explanation of the volume calculation

$$V_{\text{DepositedAlloy}} = S \cdot \underbrace{V_{\text{Aperture}}}_{\text{Known}} + \underbrace{V_{\text{Throughholealloy}}}_{\text{Measured}}$$

$$-S \cdot \underbrace{\left(\pi \cdot \frac{D^2_{Throughhole}}{4} \cdot h_{Stencil} \right)}_{Known} =$$

(more precisely)

$$V_{DepositedAlloy} = \underbrace{(S \cdot V_{Aperture})}_{\substack{Known \\ +}} \underbrace{\left(\pi \cdot \frac{D^2_{Hole}}{4} \right)}_{Known} \cdot \underbrace{h_{Alloy}}_{Measured} -$$

$$- \underbrace{\left(S \cdot \pi \cdot \frac{D^2_{Throughhole}}{4} \cdot h_{Stencil} \right)}_{Known} \quad (2)$$

S is the contraction coefficient of the paste. The paste usually contains 50 volume per cent solder alloy but it must always be checked in cases where the paste has been previously used. That is why this coefficient is needed when calculating volumes. When dealing with measured volumes, only the solder alloy thickness is measured (h_{Alloy}) not the paste thickness. Other parts of the paste are invisible to the X-ray machine. The required volume of alloy for a perfect solder joint formation is calculated according to standard IPC-7525 and [1] (Fig. 7).

$$V_{RequiredAlloy} = \left(\left(\pi \cdot \frac{D^2_{Throughhole}}{4} - A_{Pin} \right) h_{PCB} + \right.$$
$$\left. 2 \cdot \left(0,215r^2 \cdot 2\pi \left(0,2234 \cdot r + a \right) \right) \right) \quad (3)$$

To measure and calculate the hole-filling, the simplest way is
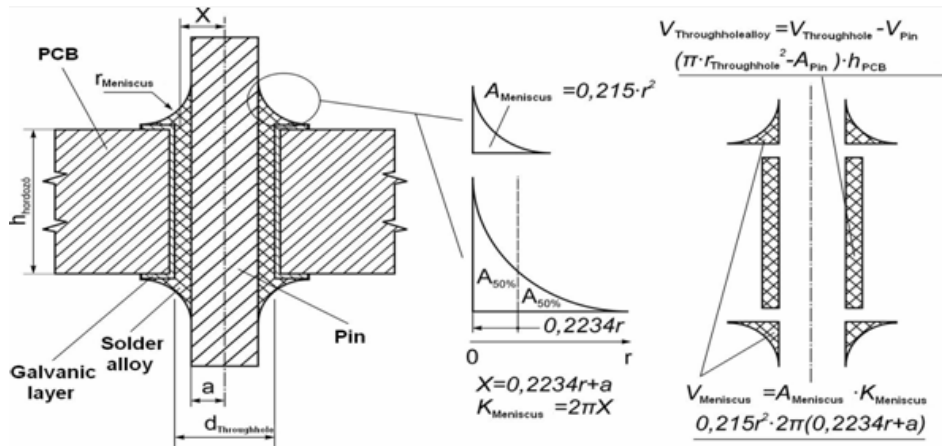

Fig. 7. Schematic of the through-hole

to use manual segmentation. With the help of Adobe Photoshop, assignment of the field of interest (FOI) can be carried out by hand. The functionality of the program enables us to calculate the average gray-scale of the hole (Fig. 8).
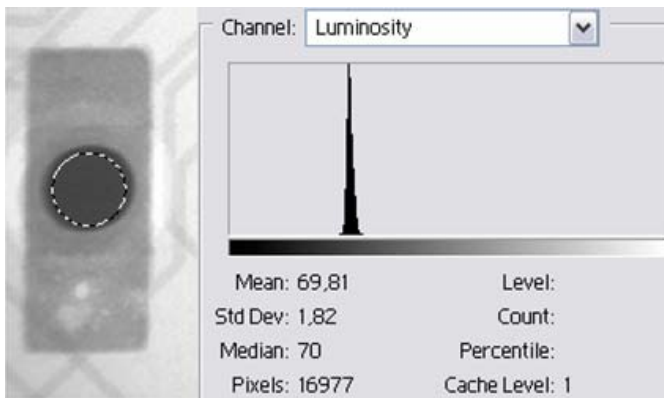

Fig. 8. Manual average gray-scale calculation using Adobe Photoshop

Of course, it would be better to make an automatic assignment of the FOI and the average gray-scale calculation.

Now let us demonstrate the mathematical approach to our method.

4 Hough transform

In case of a detect circle in a bitmap image, first consider the parametric equation of the circle:

$$r^2 = (x - a)^2 + (y - b)^2 \tag{4}$$

where a and b are the coordinates at the center of the circle and where r is the radius. For instance, the circle line consists of N points. Because the coordinates of these points are known (x, y) N non-linear equations can be formulated.

$$
\begin{aligned}
r^2 &= (x_1 - a)^2 + (y_1 - b)^2 \\
r^2 &= (x_2 - a)^2 + (y_2 - b)^2 \\
&\vdots \\
r^2 &= (x_N - a)^2 + (y_N - b)^2
\end{aligned}
\tag{5}
$$

The result of any these three equations can be defined in the three main parameters (a, b, r) of the circle. If the circle line is irregular, the solution of the three equations can end with a false result. In order to determine the accuracy of the a, b and r parameters, all the N equations need to be solved with the most likely result determining the circle, which best matches the original circle. The resulting complexity of the solution strongly depends on value N and to avoid solving system of non-linear equation circle detection, the Hough Transform can be used.

Hough Transform is a technique which can be used to isolate features of a particular shape within an image. Because it requires that the desired features be specified in some parametric form, the *classical* Hough Transform is most commonly used for the detection of regular curves such as lines, circles, ellipses, *etc*.

An image is given with a circle line. If the circle is regular, the distances between points of the circle line and the center of the circle are r. When r is known, the coordinates of the center of the circle can be determined in the following way: Draw circular lines with r radius from each point of the original circle line (Fig. 9). The points are stored in a two dimensional array called a *parameter space* (accumulator array) where the elements of the array are increased by 1 at the location of the drawn points. The term '*Values of the array*' means the number of circles which cross each other at the same location. To determine the coordinates of the center of the original circle it is necessary to find the maximum value(s) of the parameter space. If r is the unknown parameter, the complexity of transform becomes more complicated because in this case, the accumulator array is three dimensional.

5 Hole-filling measurement

Hole-filling inspection is based on averaging the gray-level values of those pixels which represent the solder alloy in the image. An X-ray plan-image of the filled hole is needed for the purposes of examination (Fig. 10).

Image processing algorithms are applied to the image to compute the volume of solder and the filling percentage of the hole. The primary objective is to determine the pixels which denote solder alloy in the image. After using some preprocessing al-
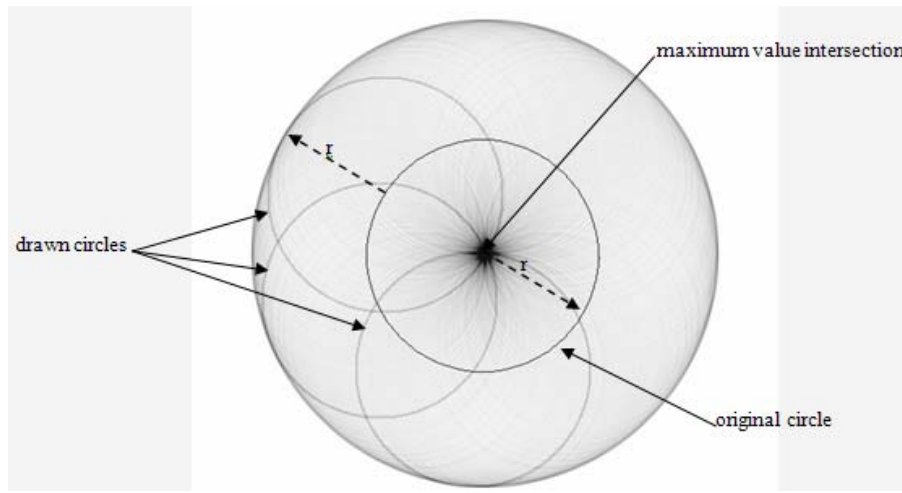
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Fig. 9. Circle detection with Hough Transform

Fig. 10. Original image of a filled hole

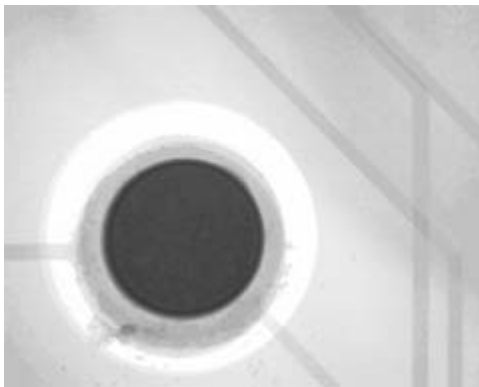**Fig. 11.** Laplace filtered image

gorithms, edge (circle) detections and circle fittings with Hough Transformation are used in the picture to locate the most important pixel areas.

5.1 Image processing

At the first stage of the image processing, the gray-scale image is converted to an intensity matrix containing values representing the intensity of the pixels scaled in the normal range of 0 to 255. A black pixel in the image is represented by value 0 and white with a full intensity value of 255. Background pixels should be removed in order to prevent an adverse hole-filling analysis.

Pixels of the galvanic layer are enough to define the boundaries of paste. This means that the values of elements in the intensity matrix can be compared with an adjusted threshold depending on value of galvanic pixels and it becomes possible to remove the entire threshold exceeding elements. So, an image is created by background removal with only the galvanic pixels remaining.

Edges in the images are the boundaries of areas with strong intensity contrasts, a jump in intensity from one pixel to the next. Edge detecting in an image significantly reduces the amount of data and filters out useless information while preserving its most important structural properties. There are many ways to perform edge detection. However, a majority of different methods can be grouped into two categories, Gradient and Laplacian.

Let us calculate the image of galvanic pixels as a function of two variables ($a[m, n]$), where m denotes the horizontal, n denotes the vertical position and a means the intensity of pixel. Edges on the image are detected by a Laplacian filter as described in [4]. Using this method, orientation-independent higher-order (second) derivative of achieved function of two variables can be calculated in the following way:

$$\nabla^2 a = (h_{2x}) \otimes a) + (h_{2y} \otimes a) = L \otimes a \qquad (6)$$

$$[h_{2x}] = [h_{2y}]^t = \begin{bmatrix} 1 & -2 & 1 \end{bmatrix} \qquad (7)$$

$$L = [h_{2x}] + [h_{2y}] = \begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \qquad (8)$$

where h_{2x} is the horizontal, h_{2y} the vertical second derivative filter and L is the corresponding Laplacian filter. Executing the convolution steps described above, the resulting edge detection mechanism is a circle which means a well defined boundary of the paste/solder alloy (Fig. 11).

The Hough Transform (HT) is used to accurately fit a circle to the detected edge within the filtered image.

Unfortunately, in case of circle detection transform, the concept of the common HT method provides too much data (chapter

4), therefore the main parameters of the circle (origin, radius) are computed with HT using line fitting algorithm.

We can analytically describe a line segment in numerous forms. However, here is a convenient equation for describing a set of lines uses *parametric* or *normal* notion:

$$x \cdot \cos \Theta + y \cdot \sin \Theta = r, \qquad (9)$$

where r is the length of a normal notion from the origin to this line and Θ is the orientation of r with respect to the X-axis (Fig. 12). HT fits straight lines onto each point of the circle line and the parameters (r, Θ) of these lines are stored in two dimensional accumulator array.

Circle detection HT (using line fitting) is based on search tangents of the circle line, but in case of using high-quality image and high resolution theta, it is not certain that we will find lines which go through only one point, therefore the modification of algorithm is necessary. After modification, the algorithm then looks for lines which go through most points. So, only hori-
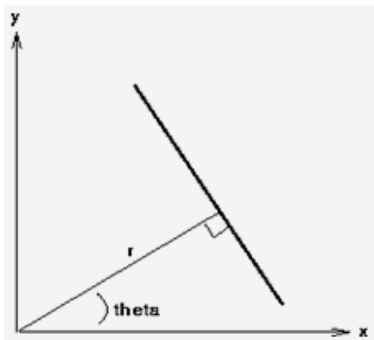

Fig. 12. Parametric description of a straight line

zontal and vertical fitted lines are added to each pixel of circle and at the same time, the parameters of these lines are stored in corresponding two-dimensional accumulator array. Lines which are best fitting the circle borderline can be established from the parameter space. Four best fitted lines are enough to compute the origin and the radius of circle (Fig. **??**). If origin and radius
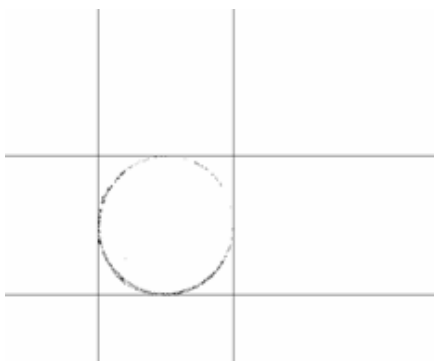

Fig. 13. Image of four best fitted lines

of the circle is known, the average gray-level value can be calculated from the original image with an averaging algorithm, which considers only the values of inner pixels of the corresponding circle (Fig. 14). With the average gray-level value
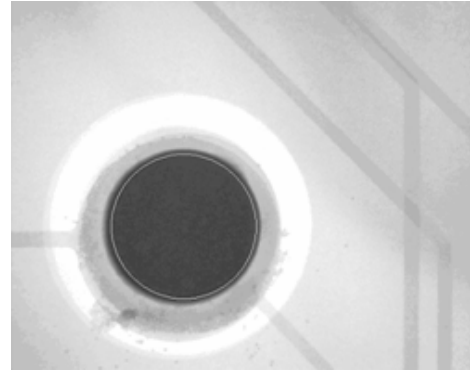

Fig. 14. Fitted circle

determined, the thickness of the solder alloy can be computed from the gray-scale characteristic of the X-ray machine. Thus, the volume of solder alloy can be calculated from thickness of alloy and diameter of the corresponding hole as demonstrated in the following way.

$$V_{Throughalbyalloy} = \pi \cdot \frac{D_{Hole}^2}{4} \cdot h_{Alloy} \qquad (10)$$

6 Computations

On completing the examinations, these values can be compared to the theoretically necessary volumes calculated in Eq. 3.

$$V_{DepositedAlloy} = \underbrace{(S \cdot V_{Aperture})}_{Known} + \underbrace{\left(\pi \cdot \frac{D_{Hole}^2}{4}\right)}_{Known} \cdot \underbrace{h_{Alloy}}_{Measured} - $$

$$- \underbrace{\left(S \cdot \pi \cdot \frac{D_{Throughhole}^2}{4} \cdot h_{Stencil}\right)}_{Known} \overset{?}{=}$$

$$\overset{?}{=} V_{RequiredAlloy} = \left(\left(\pi \cdot \frac{D_{Throughhole}^2}{4} - A_{Pin}\right) \cdot h_{PCB} + \right.$$

$$\left. 2 \cdot \left(0,215 \cdot r^2 \cdot 2 \cdot \pi \cdot (0,2234 \cdot r + a)\right)\right) \qquad (11)$$

This equation shows the two volumes that must be compared. The required alloy part shows the optimal volume of the deposited paste. Less solder alloy could cause an inefficient PIP solder joint, but according to standard IPC-A-610D, 75 % of hole-filling is acceptable. So, the minimum of the acceptable solder alloy volume is 75 % of the required volume. However, in some applications, less than a 100 % solder fill may not be acceptable.

More may be acceptable, but in this case the shunted solder paste will be more as well. This phenomenon is important to create bottom side meniscus (Fig. 15).

But if the volume of the shunted paste is significant, then an insufficient excess bottom side solder joint can be expected (Fig. 16).

There is a maximum volume when the hole is full-filled. The acceptable solder joint in this case is when the end of the pin
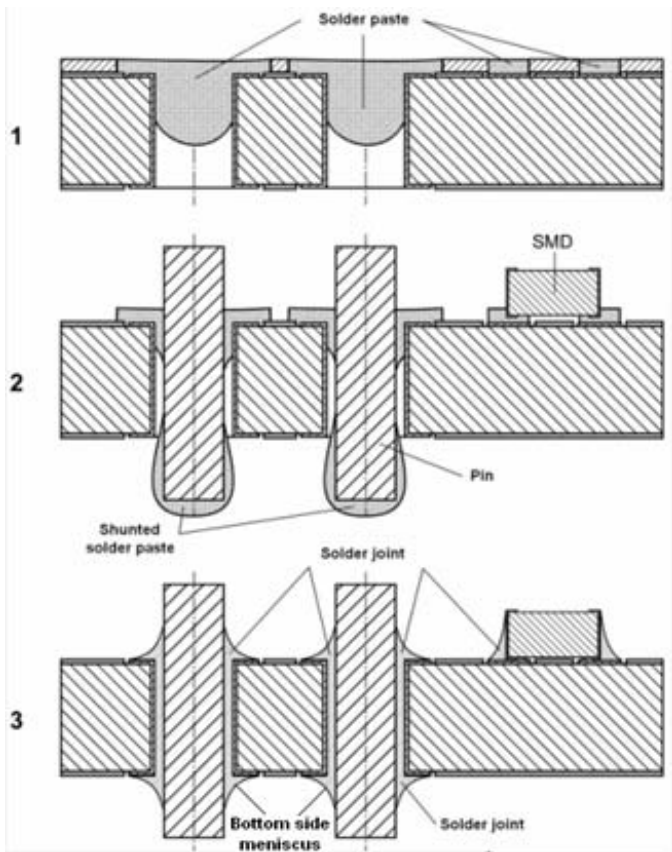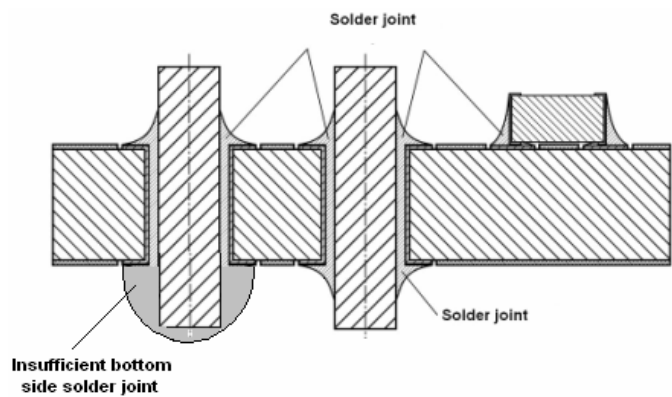
Fig. 15. Phenomenon of solder paste shunting

Fig. 16. Excess solder joint

is visible. Accurate acceptable maximum volumes cannot be given.

6.1 Measurement error

Three kinds of phenomena affect the accuracy of the measurement. The first appears when the image is created. Extreme conditions are able to cause tiny distortions meaning that the object detected is not circle but ellipse. During the circle detection, an accidental error appears. These two failures have tiny effect. The main measure failure is the relative failure of the solder alloy thickness in the function of gray-scale (Fig. 17).

7 Advantages of our method

If the three methods of measurement are compared in the function of running time then the usefulness of our method is
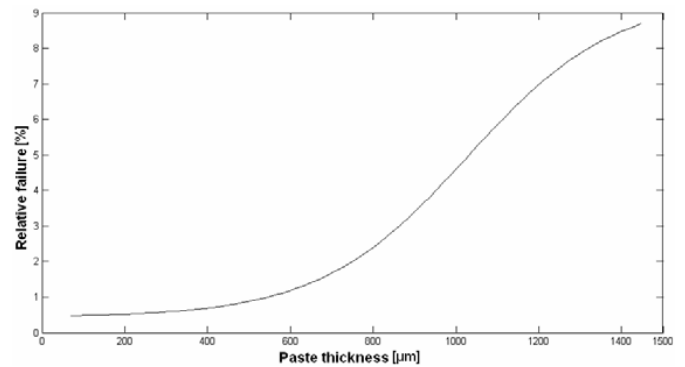
Fig. 17. Relative failure of alloy thickness

more justifiable (Table 1).

Tab. 1. Running times of the three kinds of measure

	Manual measure	Automatic measure	
		with circle detecting HT	with line detecting HT
Running time	3-4 min	2 min	1,3 sec

This brand new measure method can be 180 times faster than a manual measure, and 100 times as fast using the circle detecting Hough Transform.

Every single through-hole on a PCB can be measured, because the segmentation of the image is simple. The coordinates of the holes are available in the CAD file of the PCB. The first step is to extract a sufficient area around the hole in the function of its diameter (Fig. 18), and then to use our method.
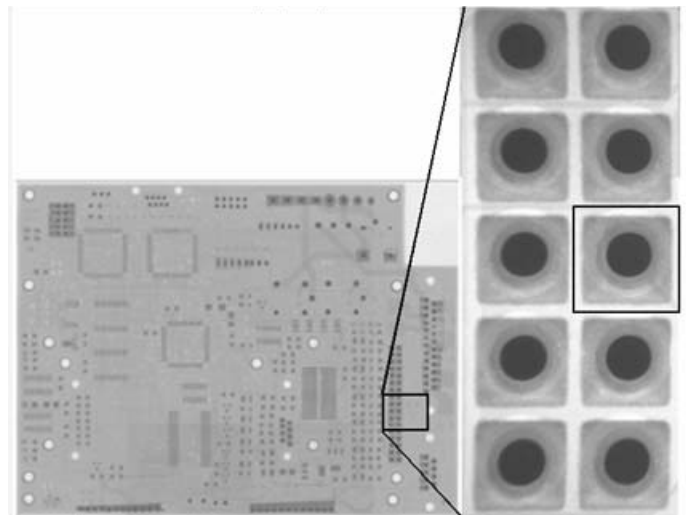

Fig. 18. FOI extraction

8 Experimental results

In our experiment, several deposited and (at a later stage by hand) prepared PIP joints were created. After deposition more paste was filled into the hole, or some was taken away to simulate possible failures (Fig. 19).
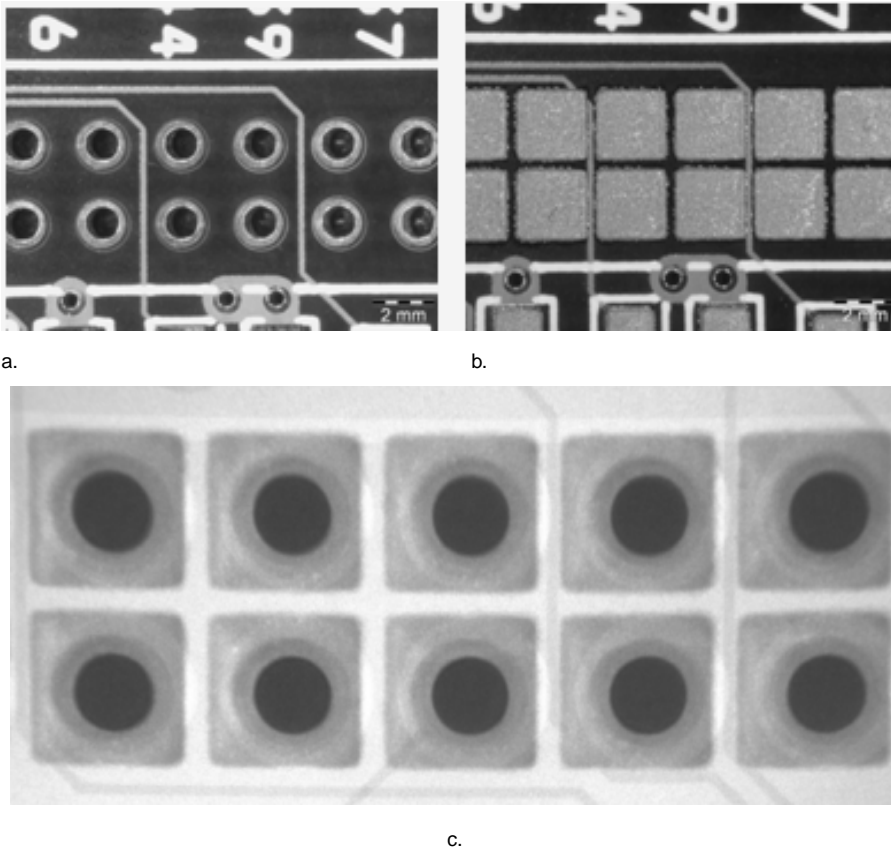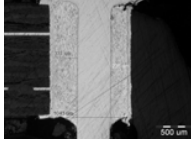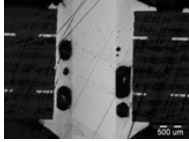
a.

b.

c.

Fig. 19. a. Through-holes *b*. Deposited paste on through-holes *c*. X-ray images of the *b* image

Tab. 2. Experimental results

	Optimal	Acceptable	Hidden failure (voids)	Failure
Preliminary qualification	Deposited volume = Required volume	Deposited volume = Required volume (*1-0.75)	Deposited volume < Required volume	Deposited volume << Required volume
Cross section of the PIP solder joint				

Using our method and calculating the volumes we were able to preliminary qualify the PIP joints. The results of our experiment are shown in Table 2.

9 Conclusion

In this paper a new method has been presented for the accurate determination of the thickness (h_{Alloy}) and volume of solder alloy in the through-hole and for the preliminary qualification of pin-in-paste (PIP) technology. The measurement characteristics of the X-ray machine used have been determined for improving the accuracy of the volume measurement. If the paste deposition is good, i.e. the paste and the solder alloy volume in the hole is sufficient, then well soldered PIP joints can be expected (Fig. 20, 21).

References

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2 **Pfluke K, H. Short R**, *Eliminate Lead-free wave soldering*, SMT (June 2005).
3 **Johnson A**, *(Speedline Technologies): From black art to modern technology*, EPP Europe, may/june 2004.
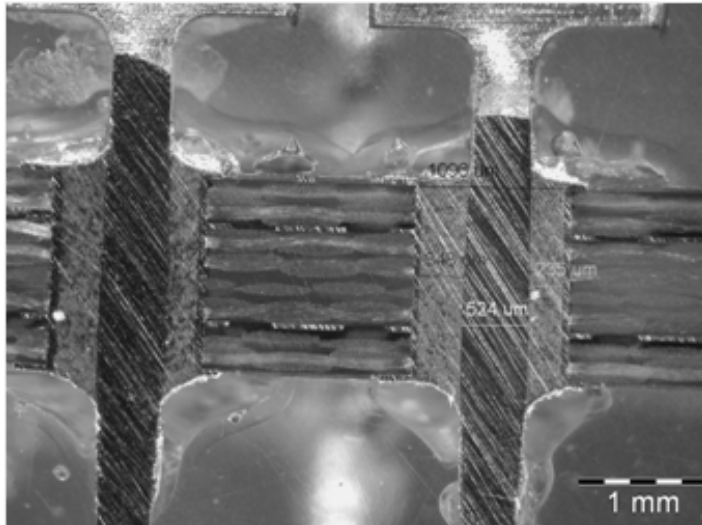4 **Székely V**, *Image processing*, Műszaki Kiadő, 2003.

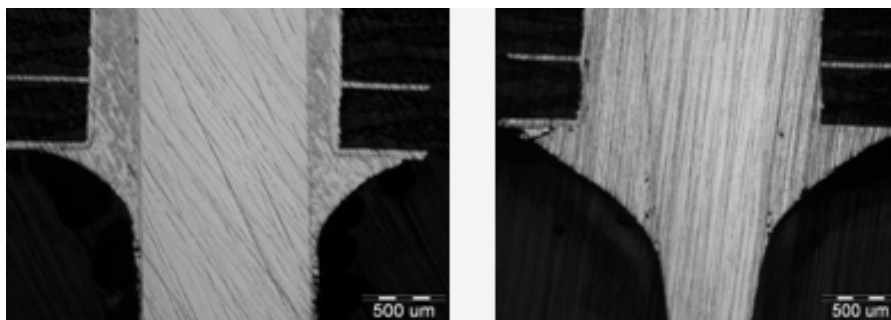**Fig. 20.** Cross-section of optimal PIP joints

Fig. 21. Perfectly soldered PIP joints, sufficient meniscus