Void defect detection in BGA solder joints using mathematical morphology

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Abstract: Voids are one of the major defects in ball grid array (BGA) solder joints due to a large amount of outgassing flux that gets entrapped during reflow. X-ray nondestructive machines are used to make voids visible as lighter areas inside the solder joints in X-ray images for detection. However, it has always been difficult to analyze this problem automatically because of some challenges such as noise, inconsistent lighting and void-like artifacts. This study realized accurate extraction and automatic analysis of void defects in solder joints by adopting a technical proposal, in which Otsu algorithm was used to segment solder balls and void defects were extracted through opening and closing operations and top-hat transformation in mathematical morphology. Experimental results show that the technical proposal mentioned here has good robustness and can be applied in the detection of voids in BGA solder joints.

Key words: ball grid array (BGA); void defect; X-ray; Otsu; mathematical morphology

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0 Introduction

Ball grid array (BGA) is a type of surface-mount packaging used for integrated circuits such as microprocessors. BGA chips adopt solder balls at the bottom of chips as pins, obtaining a lot of advantages in high interconnection, such as smaller size, more pins, bigger pin interval and better electrical performance at high speed, and therefore they are widely applied in large-scale integrated circuits. As solder joints of BGA chips are hidden at the bottom of chips when they are soldered on printed circuit board (PCB), micro-focus X-ray devices are used to inspect relevant soldering quality[1]. Solder void is a defect commonly seen in BGA solder joints, which is mainly caused when the gas produced at high temperature during soldering fails to escape, and is shown as gray-white zones within black solder ball zones in X-ray images[2]. The method for detection of solder joint voids is to calculate the percentage of void areas inside solder-ball areas. For example, soldering quality is commonly believed to be qualified if the area of a single void does not exceed 25% of the solder ball, or the aggregate area of multiple voids does not exceed 20% of the solder-ball area[3]. Studies have been conducted regarding fast detection of void defects[4-7].

Mathematical morphology was originally proposed and established by French scholars Matheron G and Serra J in the middle of 1960s during the research of gas permeability of porous media. It was mainly used for treatment and analysis of firstly binary images and then both gray and color images. Now, it has become a powerful image analysis technique by probing the image with another set of known shape called

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structuring element in fields such as image filtering, segmentation and measurement[8]. This paper presents automatic analysis and determination of void defects by using mathematical morphology to re-analyze BGA solder joint images preliminarily processed with the Otsu threshold segmentation algorithm.

1 Mathematical morphology

Mathematical morphology analyzes target shapes in images through structure elements. Its basic arithmetical units include erosion and dilation, based on which other derivatives can be obtained. Details are introduced below.

1.1 Erosion and dilation operations

A structure element in mathematical morphology is normally defined as a binary matrix, and generally, a certain element in the matrix is designated as its origin. During a morphological operation, the origin moves across every pixel in the image. In this process, the pixel corresponding to the origin is the one to be processed, and its gray value depends on the gray values of other pixels within the range limited by the structure element. A structure element can have random size and shape, normally taking its geometric center as the default origin. The size is normally set at odd numbers to guarantee single default origin, for example, matrices of 3×3 and 7×7. The shape is set by designating the values of 0 and 1 in the binary matrix, where 0 means that the pixel at the corresponding position will not participate in the operation during traversal, while 1 means that the pixel at the corresponding position will do it. The commonly seen shapes include squares, circles, diamonds, etc. Fig. 1 shows structure elements with the shapes of a 3×3 square and a diamond.

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

(a) Shape of square

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

(b) Shape of diamond

Fig. 1 Structuring elements

Suppose the pixel to be processed is $f(x,y)$ and the structure element is B. Then, dilation in mathematical morphology is defined as

$$f_{\mathrm{d}}(x,y) = f(x,y) \oplus B, \tag{1}$$

where $f_{\mathrm{d}}(x,y)$ is the resulting image after the dilation. The dilation operation is executed in this way: during the traversal of B in $f(x,y)$, the gray value of the pixel corresponding to the origin is determined by the maximum gray value of all pixels corresponding to the positions with the values of 1. In the end, dark details in $f(x,y)$ smaller than B will be removed and other dark areas will be shrunk, so as to brighten the whole image. It is equivalent to an operation for the local maximum value.

Erosion in mathematical morphology is defined as

$$f_{\mathrm{e}}(x,y) = f(x,y) \Theta B, \tag{2}$$

where $f_{\mathrm{e}}(x,y)$ is the resulting image after the erosion. The erosion operation is executed in this way: during the traversal of B in $f(x,y)$, the gray value of the pixel corresponding to the origin is determined by the minimum gray value of all pixels corresponding to the positions with the values of 1. In the end, bright details in $f(x,y)$ smaller than B will be removed and other bright areas will be shrunk, so as to darken the whole image. It is equivalent to an operation for the local minimum value.

1.2 Opening and closing operations

Opening operation in mathematical morphology is defined as

$$f_{\mathrm{o}}(x,y) = f(x,y) \circ B = [f(x,y) \Theta B] \oplus B, \tag{3}$$

where $f_{\mathrm{o}}(x,y)$ is the resulting image after the opening operation. During the opening operation, $f(x,y)$ is firstly eroded before being dilated, which means bright details smaller than B are removed firstly and then the dilation operation is applied to recover other gray values influenced by the erosion. The final result is as follows: all bright details in $f(x,y)$ smaller than B are removed completely; as for bright details bigger than B, only those that can not contain B are removed while the gray values of the others basically remain uninfluenced.

Closing operation in mathematical morphology is defined as

$$f_c(x,y) = f(x,y) \cdot B = [f(x,y) \oplus B]\Theta B, \quad (4)$$

where $f_c(x,y)$ is the resulting image after the closing operation. During the closing operation, $f(x,y)$ is firstly dilated before being eroded, which means dark details smaller than B are removed firstly and then the erosion operation is applied to recover other gray values influenced by the dilation. The final result is as follows: all dark details in $f(x,y)$ smaller than B are removed completely; as for dark details bigger than B, only those that can not contain B are removed while gray values of others basically remain uninfluenced.

1.3 Top-hat transformation

Top-hat transformation in mathematical morphology is defined as

$$f_{\mathrm{WTH}}(x,y) = f(x,y) - f_o(x,y), \quad (5)$$

where $f_{\mathrm{WHT}}(x,y)$ is the result of the top-hat transformation. The top-hat transformation is to subtract the result of relevant opening operation from the original image. In the resulting image $f_{\mathrm{WHT}}(x,y)$, the gray parts removed during the opening operation are reserved and those uninfluenced by the opening operation are cancelled out during the subtraction, resulting in the gray values close to 0. Top-hat transformation can be used to extract bright details smaller than the structure element B.

2 Experimental process and results

When BGA solder joints are detected with a microfocus X-ray device, besides the images of such joints, those of the circuit board and wires inside the chip can also be formed at the same time, which will result in complicated image structure and low contrast ratios, negatively influencing automatic extraction of void defects. Fig. 2 shows the image of a local zone of BGA chip solder joints on the circuit board, from which it can be seen that besides solder joints and voids, there are also via holes in the image. Because of such interference factors, it is difficult to extract void defects directly with a single method.

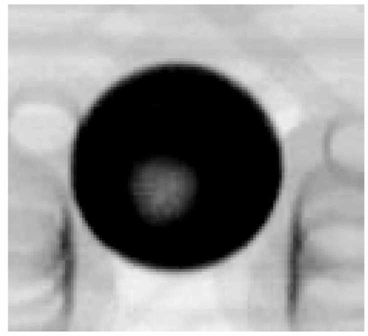

Fig. 2 The image of a local zone of BGA chip solder joints on the circuit board

A block diagram of the proposed void detection method is shown in Fig. 3. The proposed scheme consists of four components including input the image of BGA balls, extraction of solder ball, extraction of void defect and getting the result of detection. The following subsections give some details of the methodologies that were used in each step.

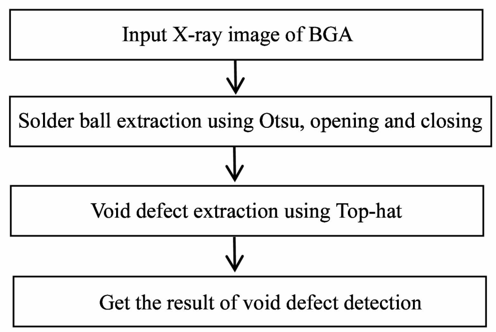

Fig. 3 Block diagram of proposed method

2.1 Extraction of solder ball zones

As BGA solder joints have bigger areas and lower gray values, apparent peaks can be easily formed in the image histogram. Therefore, relevant extraction can be done through global threshold segmentation. The Otsu algorithm is a method for threshold segmentation, firstly proposed by a Japanese scholar Nobuyuki Otsu[8]. This algorithm exhaustively searches, based on image histograms, the maximum interclass variance of both target and background pixels and then extracts targets by taking this variance as the threshold. The Otsu segmentation algorithm shows better results as to extraction of targets with higher proportion in images. Fig. 4(b) shows the result of the Otsu algorithm applied to Fig. 4(a).

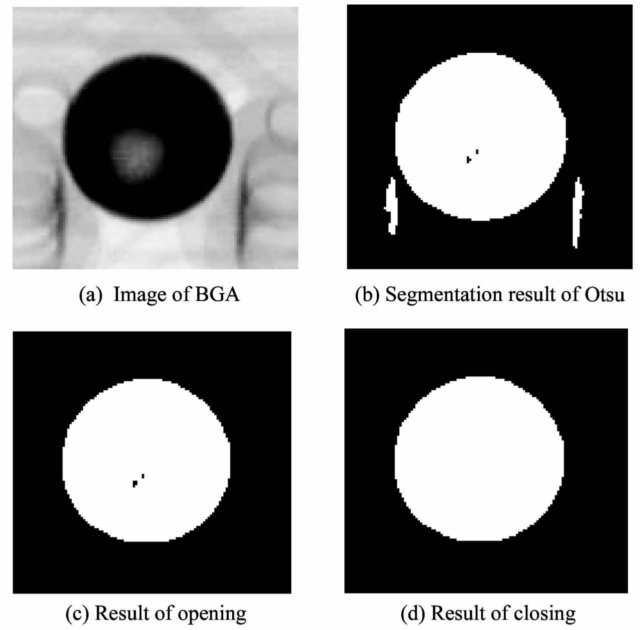

Fig. 4 Extraction of solder joints in BGA balls

From Fig. 4(b), it can be seen that all zones of solder joints were basically extracted, and that edges of via holes on the circuit board were extracted as well due to similar gray values. As zones of solder joints were bigger while interference zones were smaller, being vertical slim lines, the opening operation in mathematical morphology could be adopted to remove such interference. A square structure element of 3×11 was defined for opening operation towards Fig. 4(b), and the result is shown in Fig. 4(c), indicating that interference was totally removed.

There are some black holes in solder ball zones in Figs. 4(b) and (c). This is because the pixels in the zones of void defects have higher gray values and are processed as background. A square structure element of 5×5 was defined for closing operation towards Fig. 4(c) and the result is shown in Fig. 4(d), indicating that BGA solder joints are completely extracted through Otsu segmentation, as well as opening and closing operations in mathematical morphology.

2.2 Extraction of void defect

As void in BGA solder joints accounts for a lower proportion to the whole image, no apparent peak can be formed in the histogram, and therefore, it is difficult to extract void by directly using a global threshold segmentation method like the Otsu algorithm. However, void defects appear inside the black solder-ball zone, leading to obvious local contrast. Therefore, void defects can be extracted through threshold segmentation after void zones are highlighted by means of top-hat transformation, which is conducted by using a structure element with the size similar to the solder ball zone.

Fig. 5(a) shows the result of top-hat transformation that is conducted towards the original image by using a round structure element with the radius of 21. From the figure, the gray value of the whole image was greatly reduced, bright zones smaller than the structure element are well reserved, and void zones are more obvious against the dark background. Fig. 5(a) was processed through binaryzation with a fixed threshold of 3, and relevant result is shown in Fig. 5(b), indicating that all void zones were separated out, as well as the circuit board except solder joints. Logical AND operations were applied between Fig. 4(d) and Fig. 5(b) to obtain Fig. 5(c).

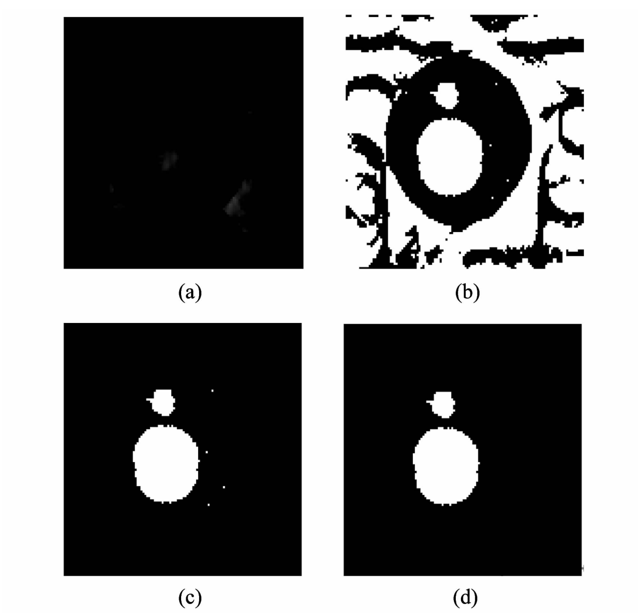

Fig. 5 Extraction of void defects in BGA balls: (a) Top-hat of ball; (b) Segmentation result of fixed threshold; (c) Result of Fig. 4(d) and Fig. 5(b); (d) Segmentation result of void defect

From this figure, only void zones inside solder balls are reserved and the circuit board expect solder joints was completely removed, as solder ball zones that are separated in the last step played as masks for the removal of interference irrelevant to solder joints.

All void zones were extracted through binaryzation after top-hat transformation, but some small noises still existed in the image. A square structure element of 3×3 was defined for opening operation towards Fig. 5(c), and relevant result is shown in Fig. 4(d) indicating noises that can not contain the 3×3 square structure element are completely removed while reserved void zones are not influenced.

2.3 Marking of detecting results

As shown in Fig. 6, graphic marks were made directly on the original image of BGA solder joints, with regard to be solder ball zones extracted in the first step and the void zones extracted in the second step. From this figure, it can be seen that the solder ball with respective void zones were extracted accurately. The areas of solder balls and void were calculated, respectively, in terms of pixels in the image.

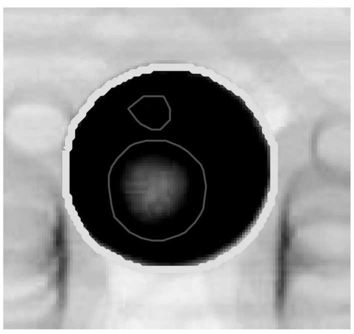

Fig. 6 Label of BGA solder joints defect detection

Table 1 shows relevant calculated results. According to the standard for quality inspection that when multiple void defects occur in a solder ball, the aggregate void area should not exceed 20% of the solder ball area, the solder ball is not qualified.

Table 1 Detection result of BGA solder joint

Area of ball (pixels)	Area of voids (pixels)	Area ratio (%)	Number of voids
4 238	1 091	25.7	2

As shown in Fig. 6, graphic marks are made directly on the original image of BGA solder joints, with regard to the solder ball zones extracted in the first step and the void zones extracted in the second step. From this figure, it can be seen that the solder ball has respective void.

To evaluate the performance of the proposed method, more BGA balls were tested and the results are shown in Fig. 7 and Table 2.

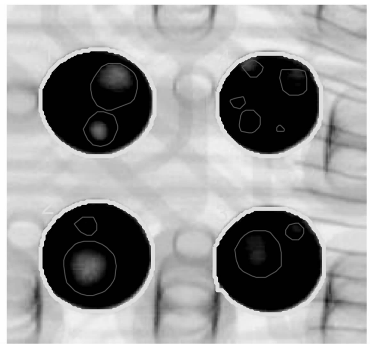

Fig. 7 Results of four BGA solder joints detection

Table 2 Detection results of Fig. 6

Ball No.	Area of ball (pixels)	Area of voids (pixels)	Area ratio (%)	Number of voids
1	4 118	1 070	26.0	2
2	4 238	1 091	25.7	2
3	4 001	836	20.9	2
4	3 670	557	15.2	5

From the table, the actual areas of the four solder balls are not exactly the same, the number of void defects in each solder ball is different, the aggregate areas of void defects in various solder balls are not the same, and the voids in different solder balls have different area ratios. According to the standard for quality inspection that when multiple void defects occur in a solder ball, only the solder ball with the number of 4 among the four solder balls is qualified.

3 Conclusion

A robust automatic void detection scheme is presented based on mathematical morphology in this paper. The proposed method is fully automated and can calculate the area ratios of the voids in order to judge soldering quality without any preprocessing. Firstly, the Otsu algorithm is used to preliminarily extract solder ball zones which will then be corrected through opening and closing operations in mathematical morphology. Next, Logical AND operations will be conducted between such zones, playing as masks, and the segmentation results after top-hat transformation to extract void zones. In this way, a complete technical plan is formed to achieve automatic analysis of void defects, which can be directly applied in engineering practice.

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BGA 焊点空洞缺陷的数字形态学检测

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摘 要： 空洞缺陷是 BGA 焊接缺陷中比较常见的一种，主要由回流焊时产生的气体没有及时排出而导致。X 射线无损检测技术可以使空洞缺陷在焊球图像上显示为白色区域供技术人员查看，但在噪声、不均匀照射、存在与缺陷类似目标的干扰下如何准确地自动提取缺陷一直是个难题。提出使用 Otsu 算法分割焊球，使用数学形态学中的开闭运算、顶帽变换提取空洞缺陷的技术方案，实现每个焊点空洞缺陷的准确提取和自动分析。实验结果表明，提出的技术方案鲁棒性强，可应用于 BGA 焊点的空洞缺陷检测。

关键词： 球阵列封装(BGA)；空洞缺陷；X-射线；Otsu 算法；数学形态学

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