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Optical Pattern Inspection for Flex PCB — Challenges & Solution

Rambabu K, Dinesh Kumar M, Vijay Kumar K, S P Nath*,
Roh, Young Jun **

** Tata Elxsi Limited, Whitefield Road, Hoody, Bangalore-560048*
India (Tel: 91-8022979123; e-mail: spnath@tataelxsi.co.in).
***LG-PERI, South Korea*

Abstract: Due to the material properties and technology advancement in printed circuit flex tapes, traditional PCB inspection algorithms using reference image cannot be used. Flex tapes are flexible circuits enabling the design and production of lighter, faster and smaller electronic products. A flex tape is made of flexible polymer film that is laminated onto a thin sheet of conductive material and etched to produce a circuit pattern. The width of fine pitch patterns can be of a few microns. Due to the material characteristics of printed circuit tapes, such as thinness and flexibility, the images captured during inspection are distorted (stretch or shrink, tilt, meandering, etc.). These anomalies and shining tape surface make the possibility of using conventional PCB inspection algorithms using referential methods for pattern inspection, difficult.

The goal of pattern inspection is to identify pattern defects — open, short, nick, protrusion, island, pinholes and dust particles. Non-repetitive and non-uniform distortions are some of the main challenges in inspecting these flexible tapes. Some of the other challenges faced during the design of the defect detection algorithm are non-uniform lighting and the gamut of sizes, shapes & orientation of defects as well as features on the printed circuit. Moreover, the algorithms need to take into account the stringent defect tolerance limits followed by the industry.

1. INTRODUCTION

There are two kinds of package substrates rigid substrate and tape substrate. Tape substrate, which is thin and flexible, is often referred to as 'Flex Tape'. It offers superior thermal and electrical performance over thicker substrates. Therefore, flex tapes find applications ranging from mobile consumer products to magneto-resistive head disk drives.

A typical flex tape substrate is a copper polyamide or copper adhesive polyamide structure used as the dielectric material. In packaging methods such as Tape Automated Bonding (TAB) and Chip On Film (COF), the chip is mounted on a flexible tape, containing the copper contact lines. The resulting package called Tape Carrier Package (TCP) provides flexible interconnects.

A tape substrate is composed of high-strength and high-temperature polymer material and hence is suitable for mobile applications, printers and disk drives. Their flexibility allows the read/write head to move over the disk, thus allowing development of faster and higher-density drives.

Flex tapes are also found in flat panel displays, like LCD (Liquid Crystal Display) and plasma screens. Several display driver chips need to be mounted around the perimeter of these displays. As these chips have flexible contacts, the contacts are connected to the front of the display and the chip is then folded and attached to the back of the display, using minimal space.

Fine patterns in the order of few micrometers can be achieved on the tapes, thus increasing the component density. Flex tape substrates for IC packages used for Tape Ball Grid Array (TBGA) and Chip Scale Package (CSP) take advantage of the fine-pitch wiring possible on flex tapes. Other salient characteristics are reduced weight, space, increased reliability & repeatability providing uniform electrical characteristics for high-speed circuitry, less power consumption and reduced assembly costs.

The paper is organized in multiple sections. Following section provides overview of current PCB inspection algorithms, their merits and demerits. Section 3 discusses challenges and complexity in algorithm design for flex tape optical inspection. The paper addresses the approaches to overcome these challenges in section 4; section 5 and 6 gives algorithm approach and flow respectively. Section 7 represents results followed by conclusion and references.

2. PCB INSPECTION ALGORITHMS

Printed circuits are inspected to isolate defects before insertion of components and soldering process. The pattern defects that affect the copper patterns on flex circuits include open (break in the conductor), short (copper bridges between conductors), nick (partial open of conductor), protrusion (copper spurs), island (spurious metal), pinhole (over etch of conductor) and dust particles.

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The current machine vision algorithms used for PCB inspection can be broadly classified into three categories based on the paper (Moganti 1996)— referential approaches, non-referential approaches and hybrid approaches as shown in Fig. 1. In referential approach, a test image is compared with the reference image for defect detection. Reference based inspection, in turn, can be divided into two types.

1. Image comparison techniques: These approaches are based on image comparison, between pixels in the test image and an idealized reference image
   a. Image subtraction– The test image is compared against the image of an ideal sample (logical XOR operation).
   b. Template matching– Comparing a template with an object in an image and it is usually performed at the pixel level as with template correlation with reference to the paper (Mandeville 1985).
   c. Phase-Only method– Standard template matching technique, based on phase only correlation between test and reference images as referred from the paper (Koichi Ito 2004).

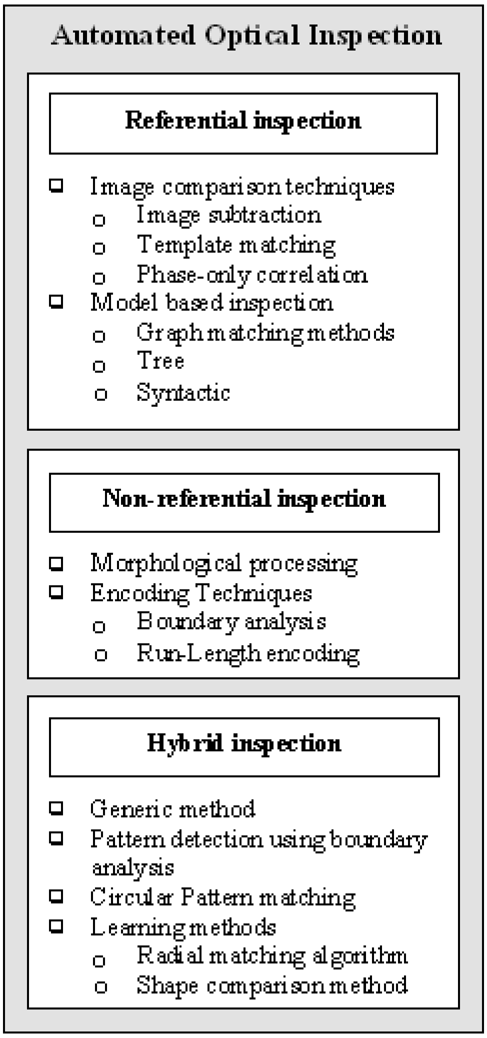

Fig. 1. Optical Inspection Algorithms Classificaion

2. Model-Based inspection methods: These approaches involve recognition of circuit features in the test image followed by a comparison against a set of reference features
   a. Graph matching method– Based on the topological/structural comparison, which compares the standard graph, obtained from the conductor and insulator image patterns of the test and reference images.
   b. Tree
   c. Syntactic

The disadvantages of referential approaches are that they are sensitive to noise, rotational and translation errors, image alignment errors and image distortion. Besides, these methods are time consuming.

In non-referential approaches, the image is transformed into a database of the patterns or features present in the image. Design rule verification, generic property verification or feature recognition algorithms are applied for defect detection. Non-referential inspection can be broadly classified into two methods:

1. Morphology processing– These transformations employ specific sequences of neighborhood transformations to measure useful geometric properties in images as referred from the papers (Louisa Lam 1992, Qin-Zhong Ye 1988).
2. Encoding techniques
   a. Boundary analysis– This method is based on the representation of the boundaries in a traceable form, followed by a rule verification procedure.
   b. Run-length encoding– Operations such as bi-image processing, pattern recognition, morphological operations, local mask operations, coordinate transformations and feature extraction using Run-length encoding (RLE) mode for identifying the defects fall into this category.

The disadvantage of non-referential approaches is that they require the standardization of feature types and cannot detect defects that do not violate the design rules.

Hybrid approaches for PCB inspection make use of both referential and non-referential approaches to overcome their inherent drawbacks. These methods can detect missing features, defects that do not violate design rules and extraneous features. Hybrid approaches can detect defects irrespective of feature size on the printed circuits. Some algorithms based on hybrid technique are:

1. Generic method– This method compares a small list of predicted feature types and locations with a list of detected features.
2. Pattern detection using Boundary analysis– This technique uses a hybrid flaw-detection method based on pattern detection and boundary analysis.
3. Circular pattern matching– In this method, a template comparator is used to perform the encoding, while the

defect detection logic is used to verify the codes to judge if the codes are contradicting.

4. Learning methods
   a. Radial matching algorithm
   b. Shape comparison method

3. CHALLENGES AND COMPLEXITY IN FLEX TAPE INSPECTION

Several challenges arise during the design of algorithms for defect detection on flex tape circuits due to the material characteristics of flex tapes such as thinness and flexibility, distortions such as stretch/shrink, tilt and meandering that may appear in the captured images during optical inspection. Distortions can also appear in the flex tapes due to mechanical feeding errors during inspection of these flex tapes, thus increasing the complexity involved in the design of approaches for inspection. Since the image distortion is non-uniform and non-repeatable, conventional PCB inspection algorithms using referential approaches cannot be used for inspection of bare printed circuits on flex tapes.

The shining surfaces of flex tape results in non-uniform contrast of the captured image. Thus inspection algorithms will not be able to process the complete image at a time for defect detection.

Defects such as open and shorts of conductor traces identified in the test image needs to be verified using a reference image. Hence test and reference images should be aligned for translation and rotational errors. These translation and rotational errors are localized errors and are non-uniform and non-repetitive.

Flex tapes enable circuits to have features with size in the order of micrometers. Typically, the smallest pattern defect size should be at least twice the size of the vision system resolution. In other cases, sub-pixel accuracy in the edge detection, dimension measurements, and alignment stages is required for identification of defects on fine pitch pattern regions. The price/performance of the computation power required to handle the extra data must be taken into consideration during the design of the inspection system.

Defects on printed circuits can be of any size and shape. They can be wide shallow, wide deep, narrow shallow or narrow deep as shown in Fig. 2.

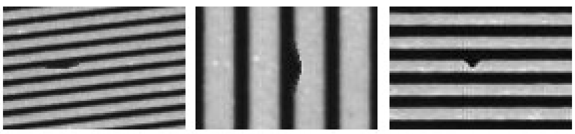

Fig. 2. (a) Deep wide protrusion, (b) shallow wide protrusion and (c) deep narrow protrusion

Identifying the design and classification rules for defect detection, independent of the size and shape of defects is a major challenge in the design of inspection algorithms. For example, the algorithm based on the Eigen value of co-variance matrix as referred from paper (C Yeh CH 2001) fails in some of the above cases.

Similarly, patterns (features) on the flex tapes can have varying size and orientation. Patterns can be horizontal, vertical or of any slope or a combination of these. Inspection algorithms should be able to identify the defects on any of such patterns and in corner areas.

The validation of a possible defect as an actual defect involves the complexity of comparing the candidate defect's width with respect to pattern and/or space width. If the defect width is greater than a factor of corresponding pattern and/or space width, then it is validated as a defect.

Image pre-processing like binarization of the image and edge detection is required prior to defect detection. Since the image contrast is non-uniform and non-repetitive, binarization as referred from the papers (Ping-Sung Liao 2001, Mehmet Sezgin 2004, Sungzoon Cho 1989) is a challenge in the algorithm design. The edge-detection algorithm should yield single pixel width edges without edge breaks. Existing gradient-based methods give edge breaks in weak pixel gradient pattern areas. Moreover, contour retrieval algorithms expand the patterns and hence modify the defects. Designing an appropriate edge detection algorithm is another challenge in the inspection algorithm design.

4. APPROACHES TO OVERCOME THE CHALLENGES

4.1 Image distortion

Due to the physical characteristics of flex tapes, translation and rotational errors may appear in the image captured during inspection. Since these distortions are non-uniform and non-repetitive, the image would need to be divided into small frames and must be aligned to the corresponding reference frames. Techniques for aligning test and reference images are:

a) Cross Correlation (Phase only correlation): Fourier transforms of test and reference image are computed as F and G using Fast Fourier Transform (FFT). The cross-phase spectrum (or Normalized cross spectrum) defined as:

$$R_{FG} = F * \mathbf{G} / |F * \mathbf{G}|, \qquad (1)$$

Where **G** is the complex conjugate of G as proved in the papers (Koichi Ito 2004, Barbara Zitova 2003). Next, the inverse transform of R_{FG} (r_{FG}) is calculated. The position of the highest peak in r_{FG} gives the translation shift between test (F) and reference images (G).

b) Pel Difference Classification (PDC)
c) Mean Absolute Difference of pixel values
d) Mean Squared Difference of pixel values

e) Integral Projection

4.2 Non-uniform contrast levels in image

To overcome the non-uniformity of contrast levels in the image, the captured test image is divided into sub-images and each frame is processed for defect detection. The actual processing window size is set greater than the sub-image frame size so that defects on boundaries of the frames are also detected. The overlapping width of the sub-images is set to be equal to the sum of the maximum deviation between test and reference image and the minimum local neighborhood window size required for defect detection analysis. Considering small frames and processing each frame individually solves the non-uniform image contrast problem.

4.3 Sub-pixel analysis for defects in Fine Pitch Patterns (FPP)

In fine pitch pattern regions of the image, sub-pixel analysis is required for identifying defects. Approaches that increase resolution of images, or sub-pixeling techniques for edge detection, measurement and alignment can be used for the analysis of defects in such regions. Today's vision systems have responded by being designed around higher resolution imagers, and have greater computing power to achieve high performance in spite of the large amount of data to be processed.

4.4 Different sizes and shapes of defects

PCB inspection algorithms should be able to detect defects independent of their size and shape. Defect detection algorithms based on statistical methods fail in identifying defects independent of their size and shape. Identification of defects should be based on local neighborhood geometry in the edge image. Defect identification design rules and classification rules based on boundary analysis techniques that analyze the local geometry can detect defects irrespective of defect size and shape.

4.5 Dust particles identification

Foreign materials may present on flex tapes during inspection. These foreign materials are called dust particles, shown in Fig. 3. Dust particles can be identified and classified based on their irregular geometry and pixel color values.

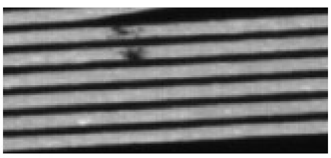

Fig. 3. Dust particles on tape substrate

4.6 Consideration of defect tolerance limit

The defect finding capability of the inspection system is evaluated by the defect tolerance limits considered during the defect analysis phase. The defect width in a direction perpendicular to the pattern is compared with a fraction of the corresponding pattern and/ or space width for defect validation.
If the defect width is greater than a factor of corresponding pattern and/or space width, it could cause current carrying capacity problems, capacitive effects, electromagnetic effects, etc., that affect the functionality of the circuit

5. DEFECT DETECTION ALGORITHM – APPROACH

This approach is a hybrid approach, which makes use of both non-referential method and referential method that are complement to each other leading to high error sensitivity, irrespective of the feature and defect sizes on flex tapes. Segmentation is used to identify regions having textual information on the flex tapes. Segmentation also identifies the fine pitch pattern regions on the flex tapes and separate design rule methods are applied to them, giving good accuracy in detecting defects on fine pitch pattern regions.

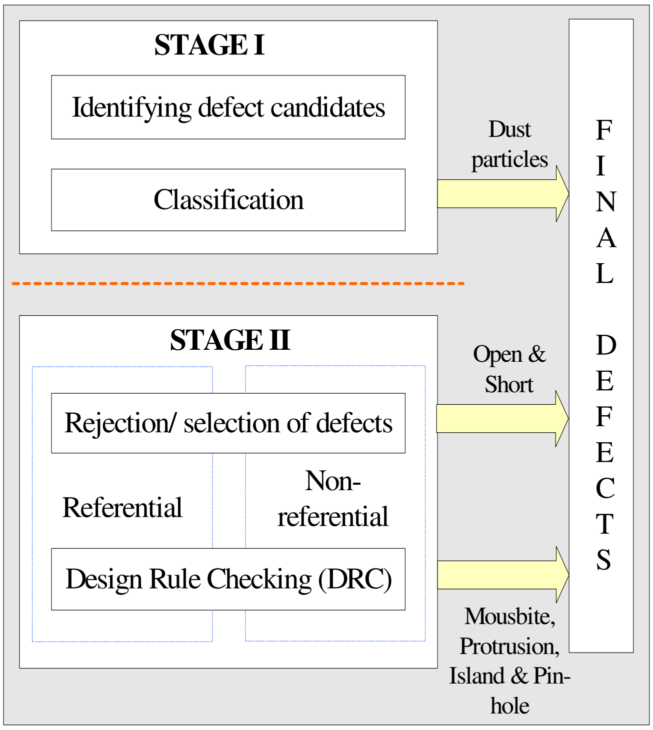

Fig. 4. Flex tape inspection block diagram

There are two stages in this approach as shown in Fig. 4, Stage I is a non-referential approach and Stage II is a hybrid approach.

Stage I: In this stage, non-referential method identifies all the defect suspicions for pattern defects. Tracking is done on either side of each defect suspicion to identify the actual defect candidates. These defect candidates are classified as Open, Short, Mouse-bites, Protrusions, Islands, Pinholes and Dust particles.

Stage II: In this stage, referential method is used to reject all obvious non-defects among the defect candidates identified by non-referential method. For example, open and short defect candidates identified by non-referential method have to be validated by the referential method. Design Rule Checking validates these classified defects by applying corresponding design rules and the validated defects are added to the final defects list. Design Rule Checking employs different methods for defects on fine pitch pattern regions and coarse pitch pattern regions.

6. DEFECT DETECTION ALGORITHM – FLOW

Defect detection algorithm for pattern inspection of flex tapes is illustrated in Fig. 5.

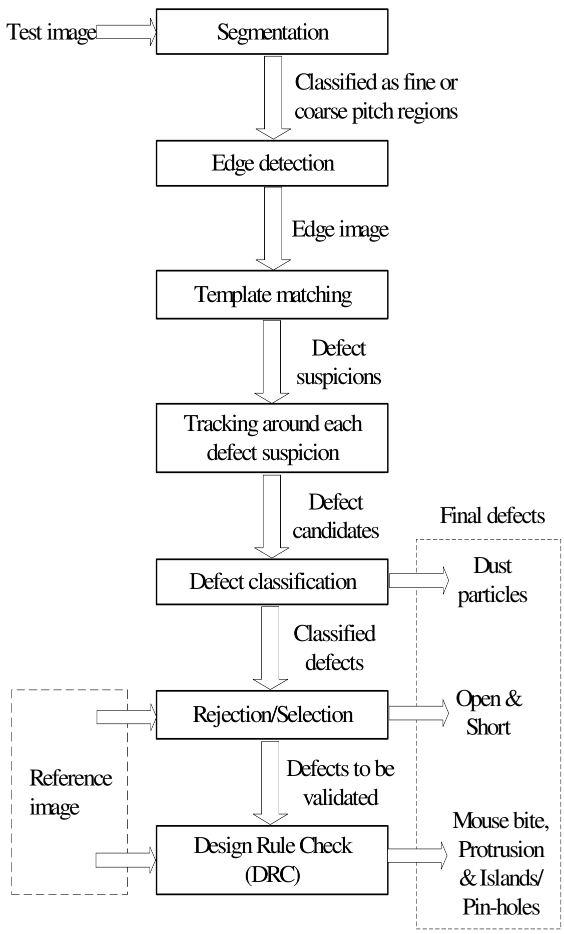

Fig. 5. Defect detection algorithm flow

6.1 Pre-processing

a) Since the complete test image of size typically 8000 X 8000 pixels (gray scale) can have fine and course pitch patterns varying from region to region, it is divided into small image frames of size 256 X 256 pixels for defect detection

b) Test image frames are selected with overlapping regions for defect detection as per (2).

   Effective image size for defect detection = Test image frame size – (Minimum width required for tracking around the defect + Maximum deviation between test and reference images) (2)

c) Segmentation is applied on each test image frame to classify it as fine or coarse pitch region and to identify textual regions in the image

d) Boundaries that have single pixel width and edge continuity are identified in the test image frames

6.2 Identifying defect suspicions

Edge image obtained in the above step is traversed and at each pixel a region of size 3X3 with current pixel as center, is compared with pre-defined templates for identifying defect suspicions. The standard templates used are as shown in Fig. 6.

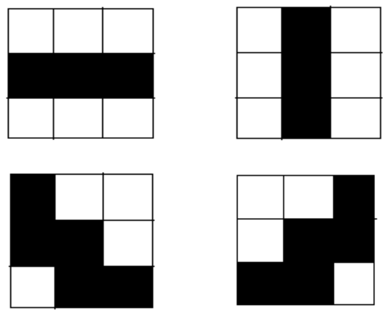

Fig. 6. Templates used for template matching

6.3 Identifying defect candidates from defect suspicions

a) Boundaries around each defect suspicion are tracked at pixel level and the pixel movement directions are noted on either side of the defect suspicion. The following 8 pixel movement directions are considered as shown in Fig. 7.

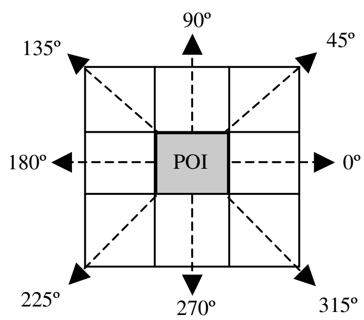

Fig. 7. Boundary tracking directions

b) These pixel movement directions are analyzed to verify the defect suspicions as defect candidates

6.4 Defect classification

a) Defect candidates identified in the above step are classified based on the following parameters:
    i. Tracked pixel movement directions around the defect
    ii. Pixel gray value of the mid point of the defect's extreme points

b) In the above step, defect candidates are classified as—Open, Short, Mouse bite, Protrusion, Island, Pinholes and Dust particles

6.5 Classifying Open and Short defects as final defects using reference image

Since there can be patterns of Open or Short defect type present in the original image, these defects needs to be verified by checking for the presence of similar features in the reference image using tracking method. All Open and Short defects are classified as final defects at this stage.

6.6 Classifying Mouse bite, Protrusion, Island and Pinhole defects as final defects by DRC

a) Design rules are used for classifying Mouse bite, Protrusion, Island and Pinhole defects as final defects based on defect width with respect to corresponding pattern and/or space width

b) Design rules for Mouse bite and Protrusion defects are: Typical one-sided and two-sided mouse bite defects are shown in Fig. 8. The design rule for mouse bite defect validation as given in (3).

$$d > 2/3 * Pw \qquad (3)$$

where, d = Effective pattern width
Pw = Pattern width

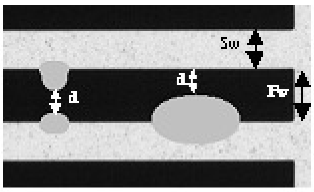

Fig. 8. Design Rule Check for mousebite defect

Typical one-sided and two-sided Protrusion defects are shown in Fig. 9. The design rule for protrusion defect validation as given in (4).

$$d > 2/3 * Sw \qquad (4)$$

where, d = Effective space width
Sw = Space width

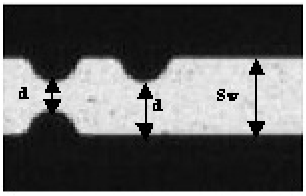

Fig. 9. Design Rule Check for protrusion defect

c) Design rules for Island and Pinhole defects are: Typical Pinhole defects are shown in Fig. 10. The design rule for pinhole defect validation as given in (5).

$$d < 1/3 * Pw \qquad (5)$$

where, d = Defect width
Pw = Pattern width

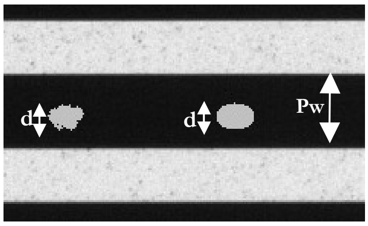

Fig. 10. Design Rule Check for pinhole defect

Typical Island defects are shown in Fig. 11. The design rule for island defect validation as given in (6)

$$d < 1/3 * Sw \qquad (6)$$

where, d = Defect width
Pw = Pattern width

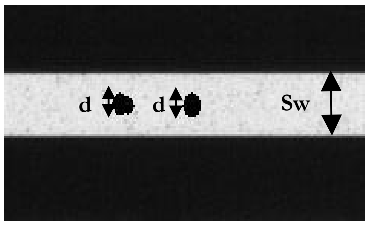

Fig. 11. Design Rule Check for island defect

6.7 Classifying Dust particles

Finally, defect candidates are classified as dust particles by checking the pixel gray value ranges and irregular geometry.

7. RESULTS

Following image shows identified defects with above explained approach. The classified defects are shown with different color rectangles as shown in Fig. 12.

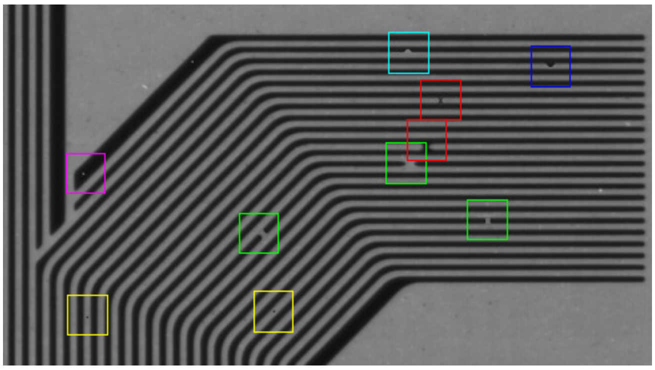

Fig. 12. Defect Identification and Classification

Fig. 13 shows identification of defects in special cases like – wide-shallow nick, both-sided nick and large short defects with different shapes and sizes

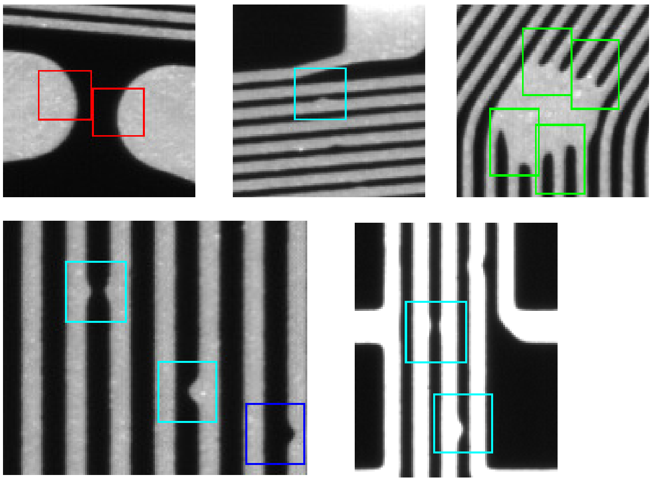

Fig. 13. (a) Large short, (b) Shallow wide nick, (c) Large open, (d) Both-sided nick and (e) Different defect shapes

This approach able to yield results more than 90% defect sensitivity in flex PCB with resolution approximately 8K X 6K, minimum pattern width of 10μm.

8. CONCLUSION

Conventional PCB inspection algorithms based on referential approaches do not work in inspection of flex tapes, due to their inherent material properties. Thus a hybrid inspection approach using both referential and non-referential approaches could be used for pattern inspection of the printed circuits on flex tapes. Statistical method based algorithms cannot be generalized for detection of all defects independent of their size and shape and patterns size on the printed circuits. Boundary technique based local neighborhood geometry analysis algorithms can detect defects of any size and shape on patterns of any size and shape. Thus the design of a complete inspection algorithm for the defect detection of printed circuits on flex-tape requires extensive research and development efforts to overcome these challenges faced by conventional algorithms. Several procedures to tackle these obstacles have been discussed in this paper.

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