2D X-RAY INSPECTION WITH MATERIALS AND THICKNESS IDENTIFICATION

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ABSTRACT
X-ray inspection systems are key tools for quality control, yield enhancement, and failure analysis of PCBs and semiconductor devices. In many cases, these capable tools provide the only non-destructive techniques for inspection of electronic components. There have been significant improvements in the X-ray inspection capabilities (both 2D and 3D) in the last several years. In this paper we report a new development that permits material and thickness information to be obtained via 2D X-ray inspection.

While absorption contrast X-ray imaging is a very powerful inspection technique, it does not exploit all of the information present within the X-ray beam transmitted through a sample. A new technology has been recently developed that, instead of simply measuring the total absorption of the X-ray beam, also enables changes in the beam energy to be resolved. This allows the effects of thickness and density to be decoupled, enabling both to be determined. This quantitative composition and thickness information can then be used to provide new levels of insight in PCB and semiconductor inspection, potentially leading the way to a new generation of X-ray inspection technology.

It is quite straightforward to accommodate this technology in an existing 2D X-ray (2DX) inspection system. Advanced software algorithms need to be incorporated and an intuitive user interface is provided.

We present an overview of this new technology and give examples of other industries where this technology is being adopted, as well as example applications for the PCB and semiconductor industries.

Key words: X-ray inspection, 2DX, 3D CT, AXI, Multi Absorption Plate, MAP, PCB inspection, material identification, thickness identification, profilometry, automated X-ray inspection, X-ray technology, PCT, CT without cutting, Large Board CT, non-destructive

INTRODUCTION

The need to inspect electronic components and assemblies non-destructively is the main driver behind the development and advancement of the X-ray inspection technology for the electronics industry. In many cases, X-Ray inspection (2D and 3D) provides the only non-destructive techniques to inspect optically hidden components and solder joints such as BGA, POP, QFN, flip chips, through holes, TSVs, micro-bumps, copper pillars, etc.

All X-ray inspection systems (2D and 3D) rely on absorption contrast imaging, where the contrast is generated by the stopping power of the sample. As such, higher density and/or thicker regions of a sample produce darker regions in a grey-scale image. X-ray inspection systems use this method to image features such as wire bonds and ball grid arrays down to a feature recognition size of 100 nm (0.1 µm).

While contrast imaging is a very powerful and widely used technique, there is significantly more information present within the X-ray beam, which, until now, has not been exploited in electronics inspection. Instead of simply measuring the total absorption of the X-ray beam, a physical structure known as a Multi Absorption Plate (MAP) can be placed in the beam path. This, coupled with machine learning algorithms, enables material type and thickness information to be acquired alongside the standard grey-scale image.

Quantitative composition and thickness information can then be used to provide more detailed diagnostics in PCB and semiconductor inspection. Applications include, but are not limited to, analysis of solder types, track thickness measurements, and conformance to quality standards.

An overview of the theory behind the operation of the MAP is given below, as well as some simple examples showing the benefits of using the MAP technology to add additional capabilities to 2D X-Ray inspection. MAP technology also has applications in the security, medical and food processing industries. Nordson Dage has partnered with IBEX to bring the benefits of this technology to the electronics inspection, including inspection of PCBs and semiconductor devices. A range of examples is presented and the authors aim to start active discussions that would generate new needs and ideas for use of the technology for non-destructive inspection of electronics systems and components.

BASIC PRINCIPLES OF THE MAP TECHNOLOGY

X-ray Interaction with a Sample

X-rays are generated using a tungsten target which produces a continuous spectrum, known as Bremβtrahlung radiation, as well as characteristic peaks at specific energies.

Adding a sample such as a printed circuit board into the beam attenuates the X-ray spectrum in the following way:

$$I(E) = I_0(E)\exp(-\mu(E)t) \qquad (1)$$

where $I_0(E)$ and $I(E)$ are the intensities of the X-ray spectra before and after the sample, respectively, $\mu(E)$ is the material-dependent linear attenuation coefficient and t is the thickness of the sample.

If $I_0(E)$ and $I(E)$ can be determined, it is possible to extract the parameter $\mu(E)$ which relates to the material type and the material thickness.

A standard CMOS detector integrates the total energy deposited into each pixel over the user-selected integration time. As such, the detector is able to measure total energy deposited per pixel but not the actual energy spectrum. This means that it is not possible to decouple the material and thickness terms in equation (1), meaning that thin, high density materials are indistinguishable from thick, low density materials in a single 2D projection.

The Multi Absorption Plate (MAP) acts like a complex "colour" filter for the X-rays by imposing a repeating modulation to the X-ray beam over a few neighbouring pixels. This modulation results in a variation in the energy distribution of the X-ray beam incident on the neighbouring pixels in a way that enables unique materials information to be obtained.

Extracting Materials Information – Simple Examples

Figure 1 shows the word IBEX constructed using a series of copper tiles with a background made up of foils of silver. The thicknesses of the foils have been selected in order to randomise the grey-scale intensity transmitted by the tiles and hence obscure the word IBEX in a standard X-ray image. Analysing the image with a MAP in place recovers the materials information. The intensities of the colouring in the bottom image of Figure 1 reflect the relative thicknesses of the tiles.

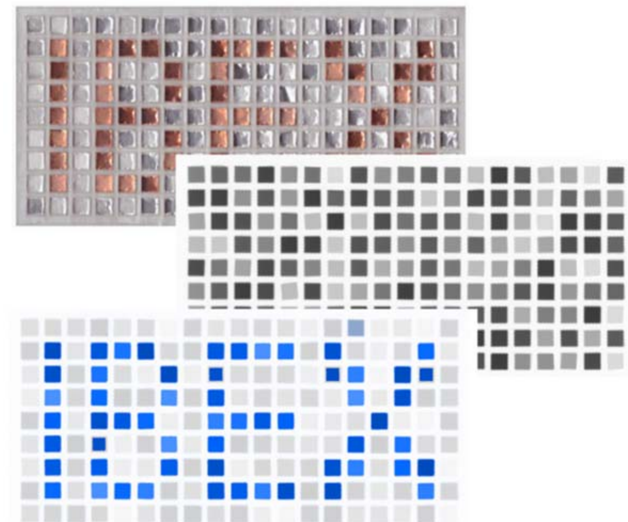

Figure 1. Optical image showing the word IBEX created as a mosaic of random thicknesses of silver and copper foils (top); X-ray transmission image showing that it is not possible to distinguish between the foils using absorption contrast alone (middle); materials contrast image showing that the missing information can be recovered using the MAP (bottom).

This materials information can be displayed to the user in terms of a basic mask identifying the materials, as an overlay of material identification on the absorption contrast image, or in the case of automated quality inspection systems as a pass/fail criterion.

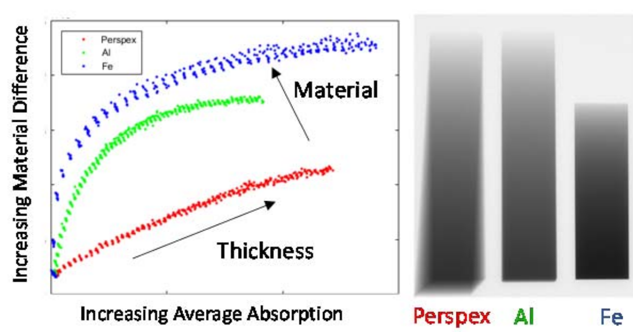

Figure 2. "Materials curves" (left) generated from training the system on the wedge samples (right).

Decisions on material type are made by reference to a "materials space" plot. The position of a point in this plot gives information on both the material type and thickness. An example is shown in Figure 2 for wedges of aluminium, iron and PMMA.

MACHINE LEARNING/USER INTERFACE

Machine learning algorithms have been developed to enable decisions to be made on material type and thickness based on the materials space plots generated from the image obtained using the MAP. The algorithms require training using a set of training standards. Once the training stage is complete, the algorithm is able to identify the material and thickness of previously unseen samples. Under ideal test conditions, the algorithm has been shown to have a misclassification rate of less than 2% and is able to identify thickness to better than 1% of the true value.

Once the MAP has been fitted to the CMOS detector, the calibration, database training and sample analysis are handled by a simple user interface which is integrated into the X-ray inspection system software. An example is shown in
Figure 3 where wedges of three materials are trained and used to identify the material types on the right of the image.

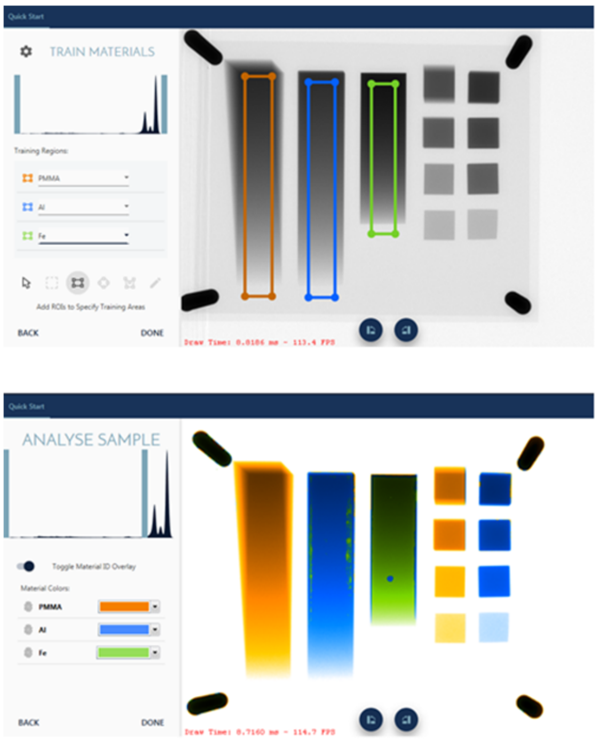

Figure 3. Screen shots showing a user interface which is designed to allow materials training (top) and identification (bottom).

The algorithm works at a rate compatible with image acquisition times and generates a standard grey-scale image as part of the process.

EXAMPLE APPLICATIONS

This article is focussed on discussing the X-ray MAP inspection technology for the electronics industry, including PCBs and semiconductor applications. In this section, we show some examples of the MAP X-ray inspection technology applied in the security and food industries. The intention is to enhance the reader's understanding of the technology and to facilitate the generation of ideas and requirements that can apply for the electronics industry.

Security Inspection

Security threats may be disguised within everyday objects such as laptops and mobile telephones, which are legitimately carried. X-ray security scanners typically use measurements taken at two voltage settings of the X-ray generator in order to generate materials information. This approach requires two scans. Using the MAP, the measurement can be reduced to a single scan at only one voltage setting.

A desk telephone, shown in Figure 4, was measured as an example of a complex object containing electronic circuitry and plastics. Data were collected at 120 kV, 0.5 mA, with a 0.5 s exposure, using a conventional, low-power tungsten X-ray source and a silicon flat-panel detector equipped with the MAP technology. Analysis of the image data leads to the materials discrimination image shown in Figure 4 (right). The colour-scheme here is one typically used in security applications: plastics and other organic materials are presented in orange; so called "poor" metals, such as aluminium, are shown in green; denser metals are shown in blue.

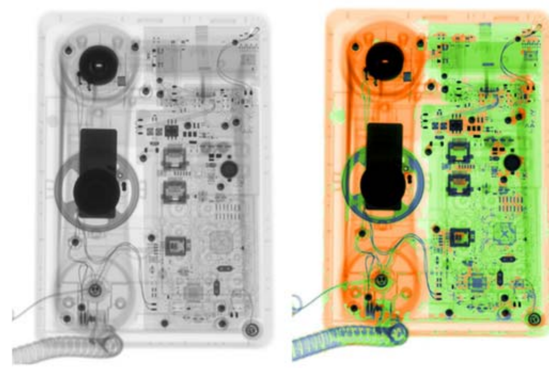

Figure 4. Left: Absorption contrast image of a telephone. Right: Materials contrast image showing plastics (orange), "poor" metals (green) and dense metals (blue).

We see the potential for the same techniques to be applied in PCB inspection to highlight inconsistencies in circuit boards and other electronic components.

Food Inspection

Detecting bone fragments in meat products is just one aspect of food safety which is important to both consumers and food producers. Fresh meat products pose particular challenges: the sample shape is not regular and there is variation from one sample to the next; the thickness of the product varies; the bone fragments are probably not visible on the outside of the sample; and the bone fragments are small compared to the surrounding flesh. X-ray absorption contrast and image recognition techniques have limited application in this field as the bone fragments have a very similar X-ray absorption signature to the meat, resulting in edges and shapes that cannot be clearly identified (Figure 5 top right).

The MAP technology enables bone fragments in chicken to be identified by virtue of their material difference from surrounding chicken breast rather than by the absorption contrast formed in a grey-scale image. Figure 5 shows an example of the detection of small bone fragments concealed inside a pile of chicken breast meat pieces.

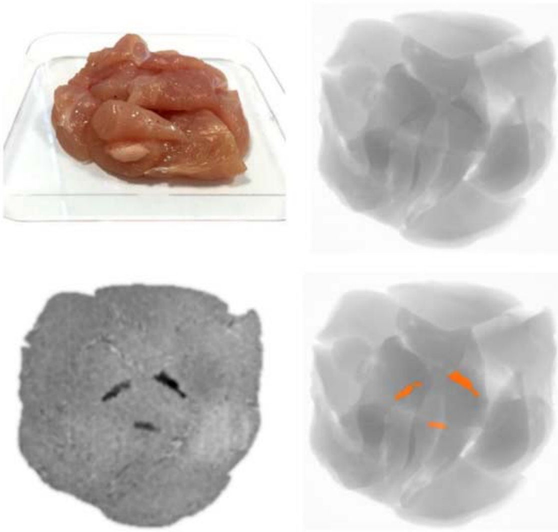

Figure 5: Top left: Chicken breast pieces with concealed bone fragments (dish 12 cm across). Top right: standard X-ray absorption image. Bottom left: materials image showing the material difference between chicken (mid-grey) and bone (black). Bottom right: materials information (orange) overlaid on the absorption contrast image to highlight bone fragments to the operator.

This type of technique is particularly well suited to automated inspection systems and may be used to identify defects or impurities within PCBs and other electronic components that would otherwise be invisible in the grey scale image.

MAP ENHANCED 2D X-RAY INSPECTION FOR THE ELECTRONICS INDUSTRY

Incorporation of the MAP technology into a 2D X-ray Inspection System

A diagram showing the general outline of a modern 2D X-ray inspection system is presented in Figure 6. The heart of the system is an extremely sharp nano-focus X-ray source allowing 100 nm feature recognition and a worry-free design that does not require filament changes through the life of the system. This is coupled with a high-bandwidth / low noise digital flat panel detector (FP). Some of the most advanced FPs have up to 6.7 megapixels with a pixel size of 50 µm running at 30 frames per second. The samples (PCBs and other electronic components) are simply placed in the sample tray. The sophisticated five-axis sample manipulation system permits oblique imaging over 140° degrees (+/-70°). The FP detector can be seamlessly rotated 360° around a point of interest. The inspection process is very simple, fast and extremely effective.

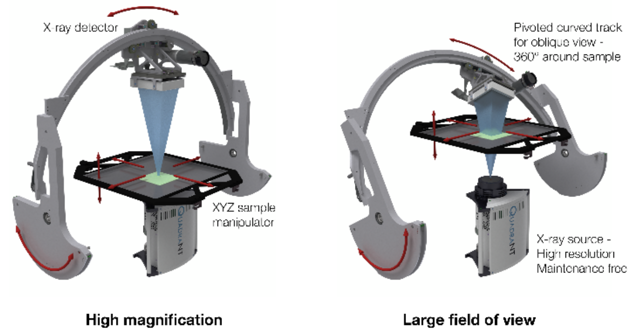

Figure 6. Diagram of a modern 2D X-ray inspection system featuring a maintenance-free sealed transmission X-ray source allowing for 100 nm feature recognition coupled with 6.7 megapixels digital FP detector.

The incorporation of the MAP hardware is very simple and straightforward. The MAP device is positioned inside the FP detector between the carbon fibre cover plate and the scintillator. Figure 7 shows an image of a MAP device installed into the CMOS detector used in the following examples.

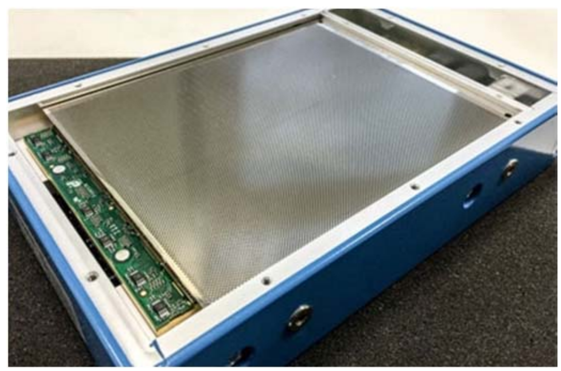

Figure 7. A MAP device installed inside a FP detector.

Copper Track Identification

The ability to recognise the presence of copper tracks is useful for a range of inspection applications. Examples include auto-registration of X-ray images to drawing files, checking for missing components and identification of broken tracks in multilayer boards. This technique is not restricted to surface layers which means that the thickness of buried tracks can also be measured. Such measurements cannot be made using standard profilometry methods.

Figure 8 shows an example of automated track identification. Here, the track information is displayed as an overlay to the grey-scale image. The board has three copper layers and each is identified by a different colour in the overlay. This type of visualisation gives us the ability to compare to a drawing file in a fast and simple way.

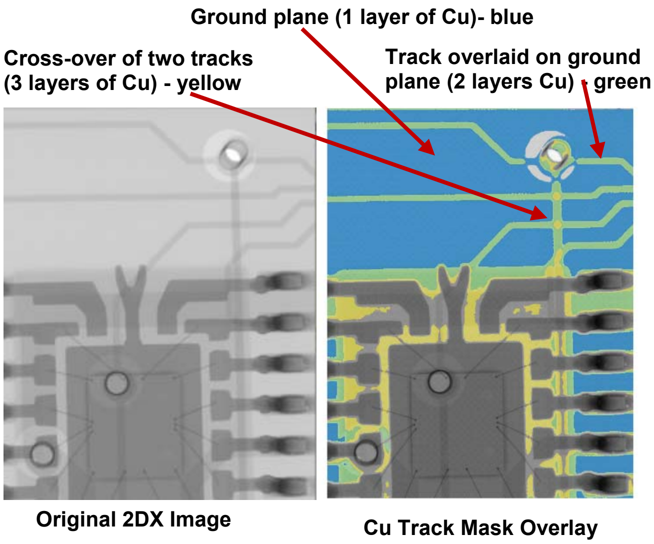

Figure 8. Example of automated Cu track identification using the energy information provided by the MAP technology. The various thicknesses of copper are shown as overlays on the grey-scale 2DX absorption image (right). Left: conventional 2DX absorption image.

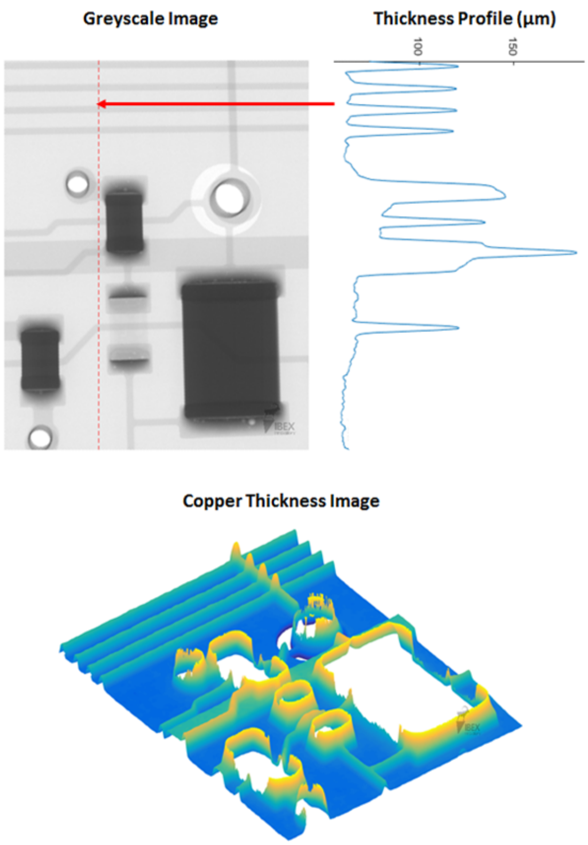

Figure 9. Illustration of how the MAP technology can be used to measure precise Cu track thickness information. This can be used to generate thickness profiles (top right) or a full three dimensional representation of the copper thickness across the PCB (bottom).

In some cases, it is important to know the precise thickness of the Cu tracks. For example, circuits involving power devices can overheat if tracks are not sufficiently thick. In the second example (Figure 9) the precise thickness of the copper is measured, enabling line profiles through copper tracks to be produced. In addition, a full three-dimensional representation of the copper thickness across the entire board can be generated.

Lead Solder Detection

With the introduction of restrictions on the use of lead-based solder, knowledge of the solder type used in manufacturing process has become increasingly important in order to ensure compliance. In this section, we show the potential of the MAP technology as a method for automatically identifying the presence of lead solder on a PCB.

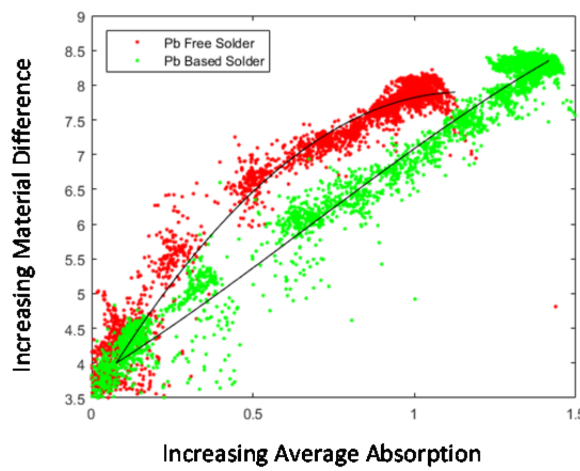

Figure 10. Materials curves for lead-free and lead-based solder samples obtained using the MAP technology installed in a Dage Diamond 2DX inspection system. The two materials curves are clearly separated, showing that a machine learning algorithm could be developed to automatically identify the presence of lead on a PCB.

Figure 10 shows the difference in materials space between an 80/20 lead/tin solder and a 99% tin/copper lead-free solder. Wedges of each solder type were measured on a Dage Diamond machine with a MAP fitted to the CMOS detector, at 160 kV and 3.9 W. The materials curves are clearly separated, showing that a machine learning algorithm could be developed to automatically identify the presence of lead on a PCB.

CONCLUSIONS

We have presented a newly-developed technology that enhances the capabilities of 2D X-ray inspection for the electronic industry. It provides additional material type and thickness information that has not been available to date in 2DX inspection.

The key to the technology is a physical structure known as the Multi Absorption Plate or MAP. This is coupled with sophisticated machine learning algorithms and training methodologies. Several cases were discussed to demonstrate applications in the electronics, security and food safety industries. Below are key enhancements gained through MAP technology:

- Enables users to visualise samples in a new way by looking at a materials image as well as a standard grey-scale absorption contrast image.
- Detection of defects and impurities that are invisible in the regular 2DX grey-scale image.
- Quantitative thickness and material information returned to the user.
- Can be fitted to most flat panel detectors.
- Near real-time operation.
- Ability to adapt algorithms for automated inspection applications.

The authors are very interested in discussions, ideas and collaborations within the electronics industry in order to focus the developments and take full advantage of this new, exciting technology.

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