ꟼP periodica polytechnica

Electrical Engineering
52/1-2 (2008) 5–11
doi: 10.3311/pp.ee.2008-1-2.01
web: http://www.pp.bme.hu/ee

RESEARCH ARTICLE

Analysis of solder joint failures arisen during the soldering process

Bálint Balogh / *Gábor* Harsányi / *Róbert* Kovács / *Csaba* Nagynémedi / *Bence* Papp

Received 2008-07-22

Abstract

The paper gives an overview of the analysis methods applied by electronic failure analysis laboratories for detection, localization and in depth analysis of solder joint failures. The paper focuses on failures that arise during the soldering process. Besides the analysis methods case studies and a few failure modes together with their inspection and root causes are also described. Optical microscopy is used for sample documentation and failure localization. X-ray microimaging can be applied to non-destructively inspect hidden joints i.e. BGA (ball grid array), flip-chip, CSP (chip scale package) bump and micro-wire. It can be also used to measure the amount of solder or voids in the joints. Inspection of PWB (printed wiring board) tracks and via metallization can also be carried out by these systems. SAM (scanning acoustic microscopy) is an effective tool to detect and to visualize delaminations or cracks inside electronics packages or assemblies. As failures are in most cases retraceable to material or compositional problems, SEM (scanning electron microscopy) together with electron microprobe analysis can be applied to find the root cause of failures.

Thorough analysis of a broken solder joint, wetting problem of cut surfaces, delamination and insufficient through-hole solder joints are presented in the paper. By these case studies not only the failure analysis procedure can be demonstrated, but also the root causes of these failures are revealed.

Keywords
failure analysis · SAM · SEM · solder joint failure

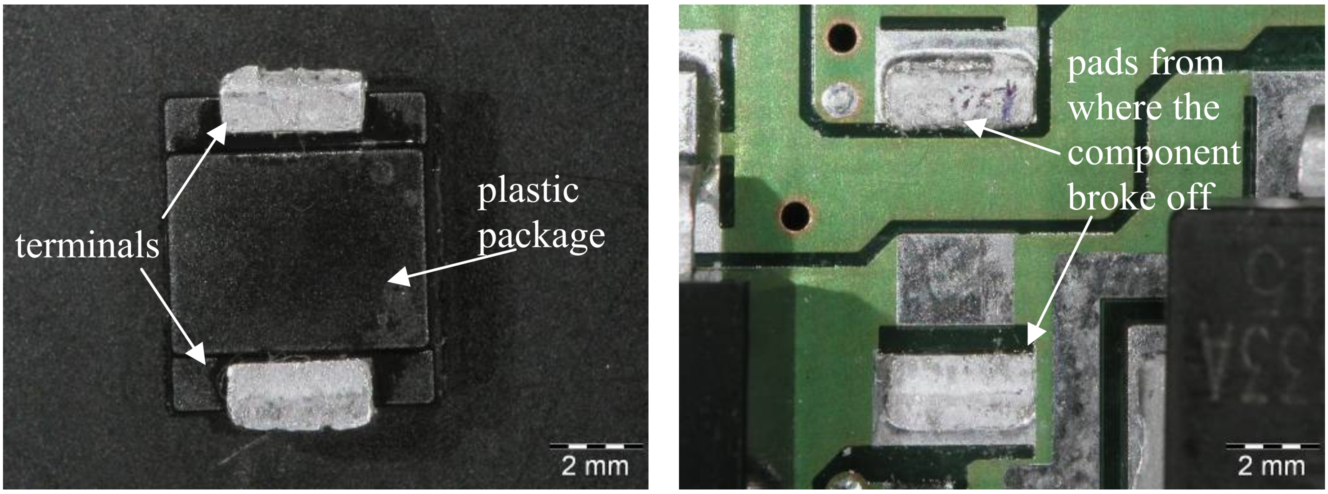
Bálint Balogh
Department of Electronics Technology, BME, H-1111 Budapest Goldmann Gy. t. 3., building V2, Hungary
e-mail: balogh@ett.bme.hu

Gábor Harsányi
Róbert Kovács
Csaba Nagynémedi
Bence Papp
Department of Electronics Technology, BME, H-1111 Budapest Goldmann Gy. t. 3., building V2, Hungary

1 Introduction

The electronics manufacturing industry applies more and more technologies together to fulfil the demands of the ever increasing functional integration of electronic devices. The development of portable electronics in the last decade was only realizable by chip scale packaging technology and by the reduction of the size of the passive components. The reliable production of these joints is a key issue of the electronic industry. Therefore companies apply AOI (automated optical inspection), AXI (automated X-ray inspection) and various electrical tests (ICT – in circuit test) to fulfil the ever increasing quality control needs of the market. The inspection methods applied in or off the production line are sufficient to filter the defective units out, but these techniques usually do not go further than recognition and possible failure localization. In order to understand the root cause of such failures, in-depth analysis is necessary. The aim of this paper is to show the methods and the processes by which the root cause of production failures can be revealed.

Reliability of solder joints has been extensively studied, especially in the last few years as new lead-free materials had to be introduced. It has been shown that isothermal ageing at elevated temperature increases the intermetallic layer, thus reduces the mechanical strength of the joints [1]. Kim et al have proven that thermal shock tests also induce intermetallic thickness growth, which results in reduced bonding strength [2]. Gong et al have shown that the residual stresses in solder joints are influenced by the reflow profile [3], the microstructure of the joints also depends on the cooling rate applied in reflow ovens [4]. It has been shown that the reflow profile influences the fatigue life of the solder [5]. As it can be seen from the previous few examples the long term reliability and the influence of the manufacturing process on the life of the solder joints have been a subject of many scientific studies. However the failures arising during the soldering process and their root causes are not described in detail in any of these papers. The authors hope, that they can start to fill this gap, by describing the most important inspection techniques and methodology applied in this field of failure analysis via several case studies.



a.

b.

Fig. 1. X-ray micrographs of a step motor
a.) without tilted detector the pin and the coil can be seen
b.) with tilted detector a solder ball behind the coil can be observed (the dot in the cross-hairs in the left bottom corner of the figure indicate the detector tilt angle)

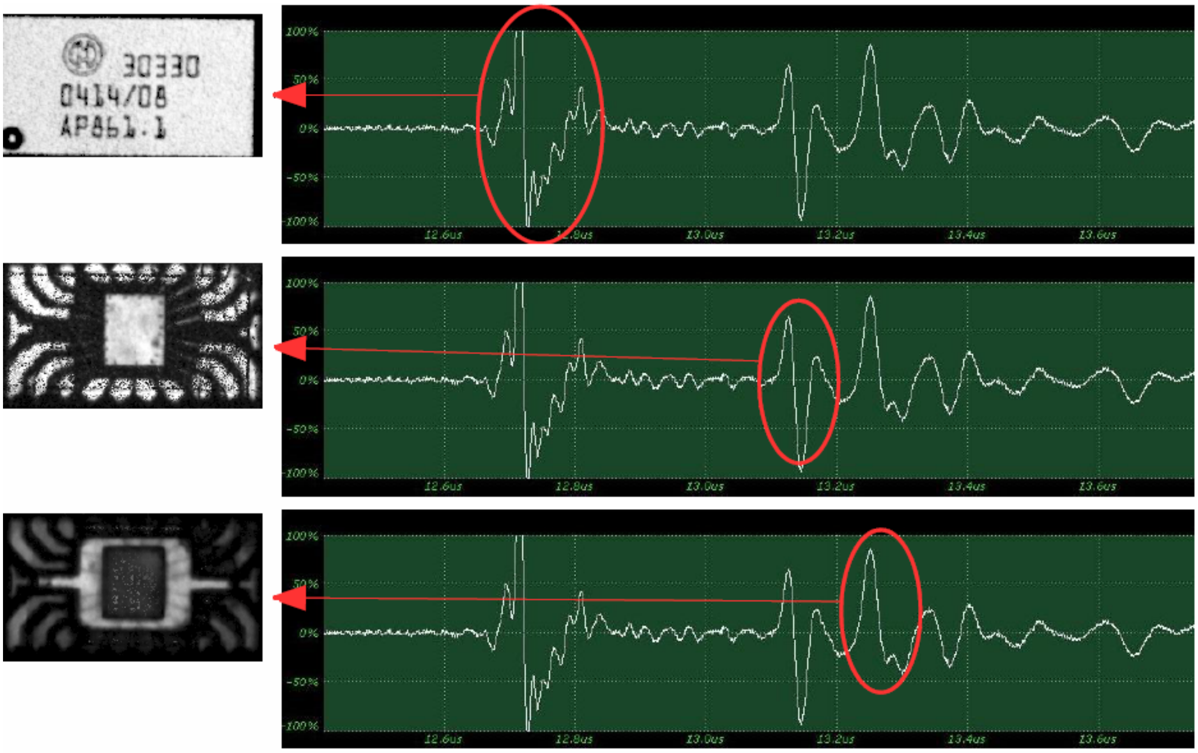


Fig. 2. Spectacular and interpretable C-scan images can be produced from different depth of the sample by choosing adequate time gates or windows of the A-scan time diagram.

2 Experimental

This section introduces and describes the methods and equipments applied for electronic failure analysis inspections. The described equipments are used by the authors during their everyday research work.

2.1 Optical microscopy and microsectioning

First and foremost the state of every sample has to be inspected by optical microscopy. This is not only necessary for deciding the further analysis methods to be done, but also important to document the state of the sample as received [6].

Two types of optical microscope were applied for the analyses described in the 3 section: Olympus SZX9 stereo microscope and Olympus BX51 upright microscope. These two types of microscope are usually needed for a complex analysis. The stereo microscope provides a sufficient field of view and depth of focus for the investigation of assembled printed circuits. In this case up to several mm height differences can be present between the level of the pad surfaces and the top of the solder joints on the component terminals. However the achievable magnification with these systems is rarely above 100x, so they cannot fulfil the needs of the metallographic analysis of the microsectioned solder joints. For such purposes upright or inverted microscopes can be used. The working distance of the objectives and thus the depth of focus can be as low as a few 0.1 mm, but the magnification can go up to 1000x.

2.2 SEM – Scanning Electron Microscopy

Scanning electron microscopy is a widely used and well known technique, which provides magnifications up to several 10.000x while the depth of field can remain in the mm range. All this is achieved while an electron beam is scanned across the surface of the sample. As the electrons strike the sample, a variety of signals are generated i.e. secondary and back scattered electrons, characteristic X-ray, Auger electrons and bremsstrahlung.

Secondary electrons (SE) are detected only from the top 5-50 nm of the sample, so a very high resolution image can be produced where the surface morphology can be observed in great detail. Back scattered electrons (BSE) are bounced back from the nuclei. The information depth, which depends on the atomic number and the accelerating voltage, is in the μm range. The contrast in the produced image is determined by the atomic number of the elements in the sample. The image will therefore show the distribution of different chemical phases in the sample. Because these electrons are emitted from up to a few μm depth of the sample, the resolution in the image is not as good as with secondary electrons.

Interaction of the primary beam with atoms in the sample can cause shell transitions which result in the emission of X-ray characteristic of the given element. Detection and measurement of the energy permits elemental analysis (Energy Dispersive X-ray Spectroscopy or EDS or EDX). EDX can provide rapid qualitative, or with adequate standards, quantitative analysis of elemental composition with a sampling depth and lateral resolution of 1-2 μm. X-rays may also be used to form maps or line profiles, showing the elemental distribution in a sample surface [6–9].

A Philips XL-30 SEM was applied in the later described inspections.

2.3 X-ray microstructure inspection

X-ray inspection systems are widely used by electronics manufacturers in or off the production line to control the quality of hidden solder joints of BGA, CSP, QFN (quad flat no-lead), and flip-chip components. The imaging method is always transmissive, the sample being placed between the X-ray source and the detector. The X-ray absorption of the materials that make up an electronic device is different thus the detected X-ray intensity can be converted to a grey scale image, where the darker areas indicate higher absorption regions. The image can later be post-processed to generate more spectacular or interpretable visualizations. The latest systems can even produce 3D CT (computer tomography) images, which can be interpreted by less experienced users as well. The possibility to view a sample from different angles is not only necessary for 3D images, but also in traditional imaging technologies, since the shape of solder bumps, the position of a broken net in a multilayer structure, via metallization can only be qualified in tilted images. A bulky component can also block the X-rays. Thus to inspect features below them tilted views are desirable, as it can be seen in Fig. 1.

Automation features i.e. amount of voids, circularity analysis of bumps are available. However the identification of failures (opens, shorts, solder meniscus problems, improper wire bondings) still needs human control [6].

A Dage XiDAT6600 X-ray microstructure inspection system was applied to the analyses described below. The main parameters of the system are:

- open X-ray tube
- W target
- accelerating voltage up to 160 kV
- movable detector: up to 45° tilt angle and complete 360° rotation around axis Z

2.4 SAM – Scanning Acoustic Microscopy

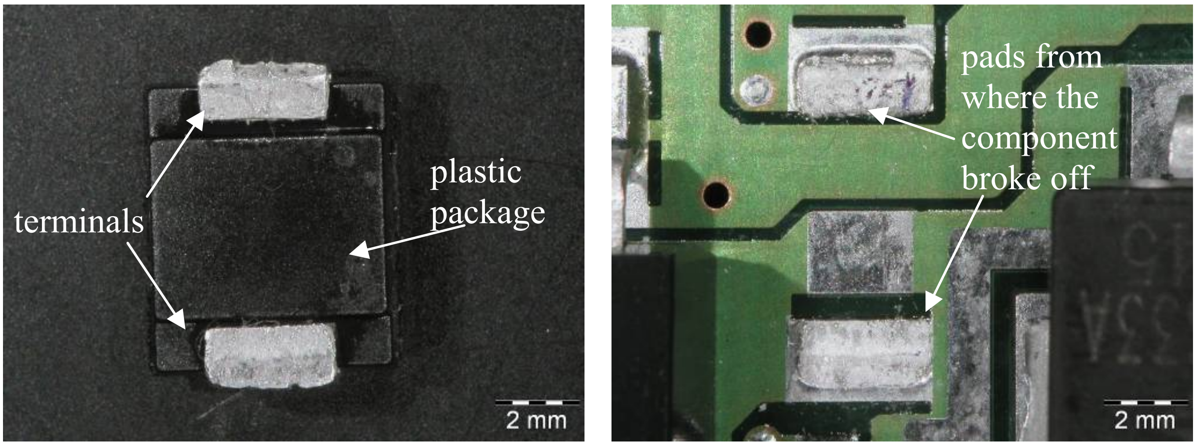
SAM is a non-destructive imaging method for evaluating inner structure failures. It is based on two important properties of the ultrasound:

- sound waves can be focused,
- a portion of the waves reflects at the boundaries of different materials.

In general, scanning acoustic microscopy is used in microelectronics materials research, product development, production process control, quality assurance and failure analysis. Some examples for the defects that can be detected with SAM:

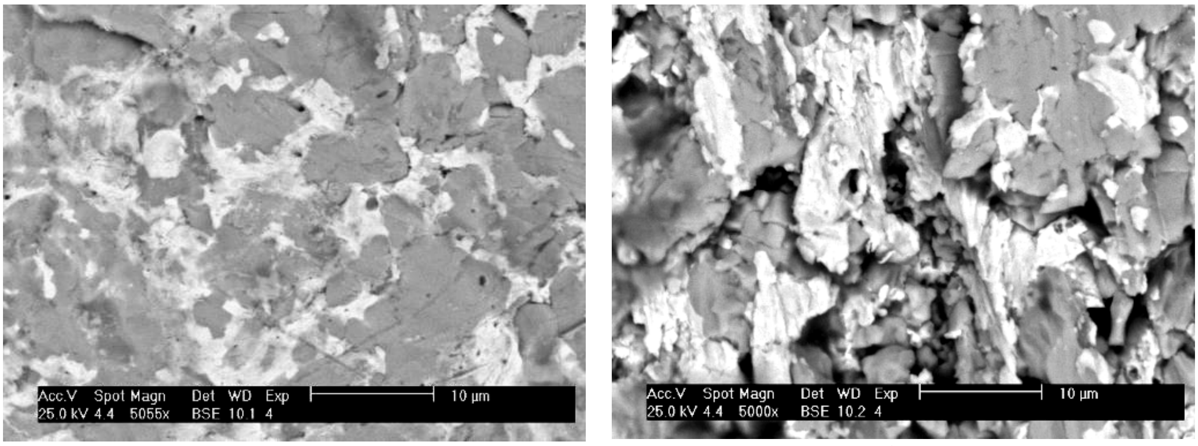
- die crack, die tilting, voids and cracks in the packaging material of plastic encapsulated ICs
- delamination of the packaging material from the die, from the leads or from the die-pad
- voids in the underfilling material of flip chips, CSPs and BGAs
- harmful voids in the hermetic sealing of ceramic packages
- flaws in TAB tapes, PWBs.

A scanning acoustic microscope can be used in pulse echo or through transmission modes. The inspection signal pulse is generated by a transducer, which can afterwards act as receiver to detect the reflected echoes. The transmitted signal can be used to check the data of the reflected image, but unlike the echo it does not provide depth information. To characterize the propagation of sound waves in a certain material, the acoustic impedance (Z) is introduced. 'Z' is the product of the sound's velocity (c) in



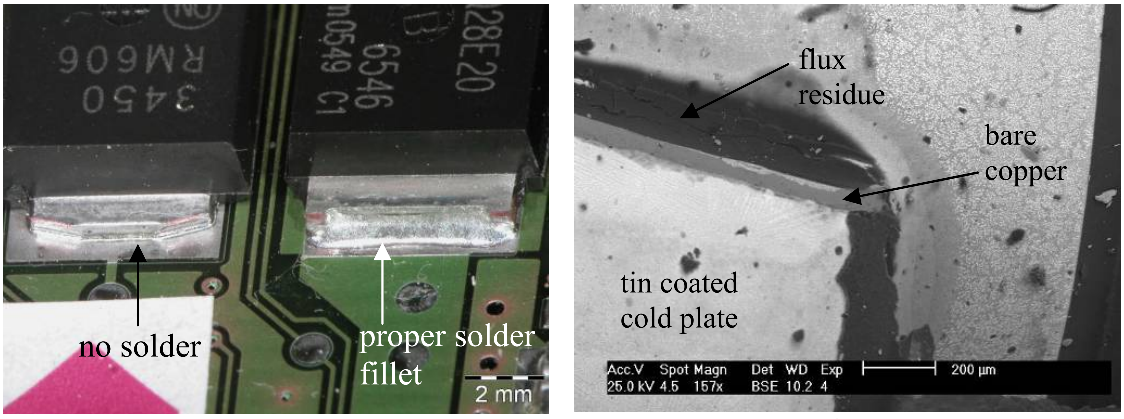
a. b.

Fig. 3. a. Broken off SMD diode;b. Corresponding pads on the PCB



a. b.

Fig. 4. High magnification back scattered electron micrograph of the even (a) and the rough (b) fracture surfaces of the solder joint.



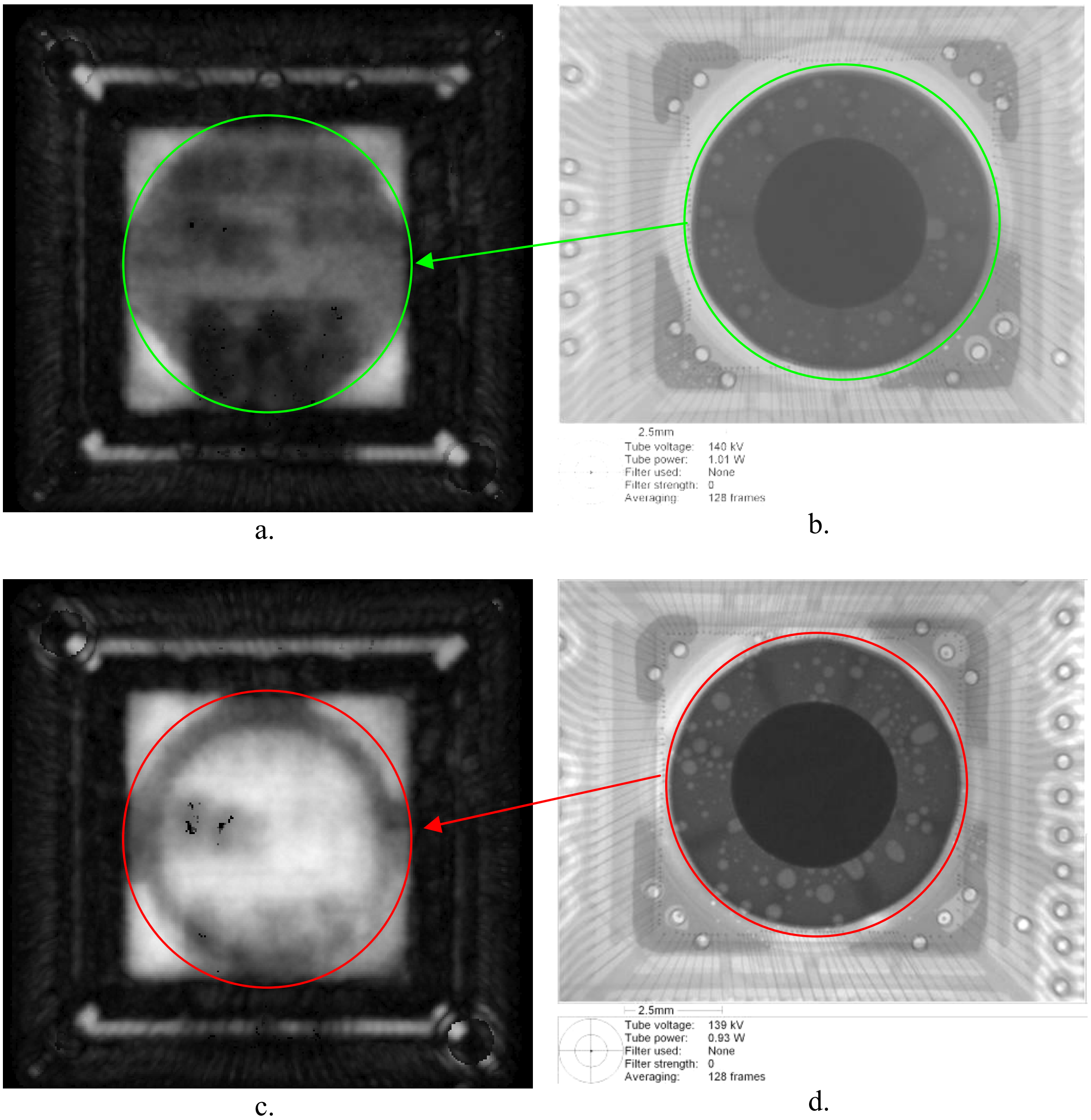
a. b.

Fig. 5. Wetting problem of a FET cold plate.
a. Optical microscopic image of two FETs. No solder fillet can be observed on the left hand side.
b. BSE-SEM micrograph of the defective solder joint. The bare copper cut surface can be observed.

the material and the density (ρ) of the material. As ultrasonic waves propagate from one material into the other the acoustic impedance changes suddenly at the interface. Because of this sudden change, a portion of the waves' energy is reflected from the boundary. As the wave propagates from a material with Z_1 acoustic impedance into one with Z_2, the amount of reflected (R) and transmitted (T) energies can be calculated from the acoustic impedances [10]:

$$R = \frac{Z_2 - Z_1}{Z_1 + Z_2} \tag{1}$$

$$T = \frac{2 \cdot Z_1}{Z_2 + Z_1} = 1 - R \tag{2}$$



Tube voltage: 140 kV
Tube power: 1.01 W
Filter used: None
Filter strength: 0
Averaging 128 frames

Tube voltage: 139 kV
Tube power: 0.93 W
Filter used: None
Filter strength: 0
Averaging: 128 frames

a. b. c. d.

Fig. 6. Comparison of X-ray and acoustic micro imaging.
a. SAM micrograph – good sample, no delamination;
b. X-ray micrograph – good sample
c. SAM micrograph – bad sample, delamination in the centre;
d. X-ray micrograph – bad sample, no defect can be detected

In acoustic microscopic terminology the ultrasound signal detected above one point of the sample is called A-scan. A typical waveform can be seen in Fig. 2. The first wave corresponds to the reflection on the top of the package, and then the ultrasound travels undisturbed until it reaches the top of the silicon die. The third wave is not separated too far from the second as it is produced by the reflection from the die attach layer. So called C-scan images can be produced by selecting a time gate on the A-scan and scanning the whole area of the sample. The grey scale of each point on the C-scan is proportional to the highest amplitude within the chosen time gate. This way a "horizontal cross-section" of the sample can be made non-destructively, as long as immersion into the coupling material, de-ionized water, does not harm it.

A Sonix HS 1000 type SAM was applied to the analyses described later. A wide range of transducers from 10 to 300 MHz can be applied with this system. The translation stages, which move the transducers, provide lateral resolution down to 10 μm.

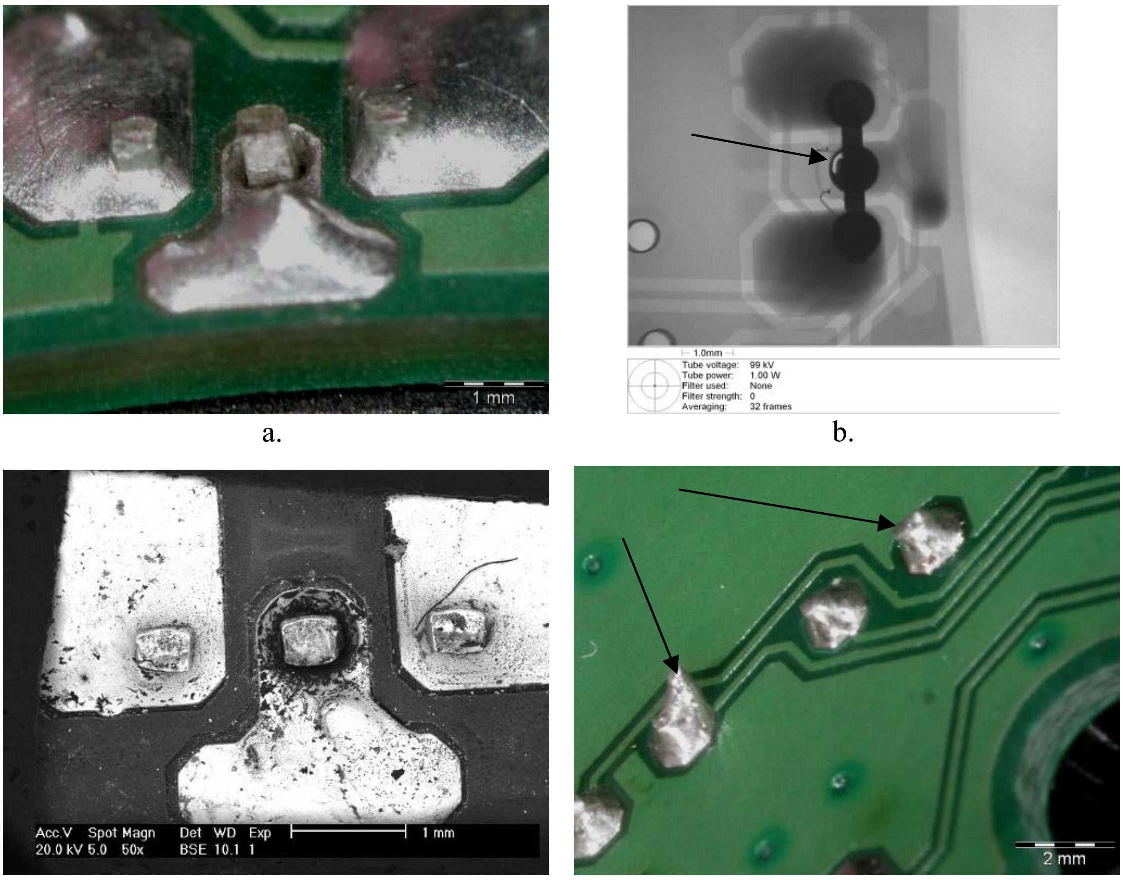
3 Case studies

Through the following four case studies the application of the above described analysis techniques and the methodology of solder joint failure analysis can be presented. All of the described failures were detected by one of the inspections during the manufacturing process and were sent to BME-ETT for further, in-depth analysis to reveal the root cause of these failures.

3.1 Broken solder joint

The two solder joints of an SMD diode were found broken on an assembled circuit (see Fig. 3). The aim of the analysis was to reveal what reasons could have led to the low joint strength.

By optical and scanning electron microscopic analysis even (Fig. 4a.) and rough (Fig. 4b.) fracture surfaces could be observed. EDX analysis revealed compositional differences be-



a.

b.

c.

d.

Fig. 7. a. Optical microscopic image of the non-wetted pin; b. X-ray micrograph, the solder did not completely fill the via; c. SEM micrograph, high amount of contamination can be seen around the non-wetted pin; d. The arrows indicate solder flags on other pins of the same PCB.

tween these two regions. Where rough fracture occurred the tin-lead ratio was eutectic, while in the even areas the relative tin content was higher, 70.25 weight%.

The even surfaces indicate that no proper joint formed, that in these regions no mechanical contact was present between the pad and the component terminal. Relatively high amount of voids was also present in the rough areas, which also decreased the strength of the joint. Since no contamination was detected, the reason of such improper joint formation may have been in the reflow temperature profile [11]. Especially as the component is placed between two large heat sinks, the temperature in this region could be lower than in other areas of the PCB, thus the short time a solder in liquid form will not have permitted proper joint and intermetallic formation.

3.2 Wetting problems of cut surfaces

Component manufacturer usually use copper as base material for lead frames, heat sinks and die pads. These are coated by tin or tin-lead to enable the solderability of the component leads. For technological reason the components are batch processed in the same lead frame and they are only cut out at the end of the manufacturing process. Thus the cut surface on the front of the leads is not covered with tin and can cause wetting problems as shown in Fig. 5.

The surface without coating was not wettable, so the complete amount of solder wetted the bottom of the cold plate and cannot be observed in the images. The high amount of organic material around the cold plate are flux residues. Such wetting problems can be due to either component storage condition or low flux activation.

3.3 Detection of delamination

X-ray microscopy is a sufficient tool to quantify the amount of voiding and to analyze the shape of hidden (or not hidden) solder joints. However it is not capable of detecting cracks or delaminations, since these features do not produce X-ray absorption differences. In Fig. 6. SAM and X-ray micrographs of two QFPs can be seen. This component needs extensive cooling, thus its bottom is soldered to a rivet, and the solder joint areas are indicated by the circles. The darker region in the middle is the rivet itself, while the solder joint is larger in diameter.

The component shown above (Fig. 6a, b) passed the load test, while the one below (Fig. 6/c, d) failed due to overheating. The X-ray images do not show significant difference between the two components, while the C-scan acoustic micrographs reveal the reason of the insufficient cooling of the lower component. The solder joint is delaminated from the bottom of the component, which is indicated by the bright area in the middle.

3.4 Insufficient through-hole solder joints

The optical microscopic inspection (Fig. 7a.) showed no solder fillet at one of the three pins of a through-hole component. The X-ray analysis revealed that the solder is missing from the whole length of the hole, since a very bright area can be seen where it is marked by the arrow in Fig. 7b.

SEM-EDX analysis showed significantly higher amount of organic material on and around the non-wetted pin as at the others. Based on this one could suspect that the wetting problem was caused by contaminations. However this cannot explain why no solder can be found inside the half of the hole. Observing other pins on the same PCB solder flags can be discovered as in Fig. 7/c. The presence of these solder flags indicates that the separation from the selective solder wave was not optimal, thus it could not only form such spikes but could also suck back too much solder from the defective pin, even removing most of the solder from inside the via. The detected organic contamination is most probably flux residue.

4 Conclusions

Besides the research of long term reliability of solder joints, the analysis of failures arising during the manufacturing process is also necessary. The failures can be filtered out in the production line by AOI, AXI and ICT. For in depth analysis to understand the failure and its root cause further techniques are needed. The methodology applied by the authors is:

1. Optical microscopic inspection to localize, characterize and document the failure.
2. X-ray microimaging to non-destructively inspect the shape, solder and void amount of hidden and not hidden joints.
3. SAM can be applied when delaminations or cracks are suspected to be present.
4. SEM-EDX analysis can reveal problems that can be deduced to contaminations, oxidations or other compositional failures.

References

1 **Yoon J, Lee C, Jung S**, *Growth Kinetics of IMC Formed between Sn-3.5Ag-0.75Cu BGA Solder and Electroless Ni-P/Cu Substrate by Solid-state Isothermal Aging*, Materials Science Forum **449-452** (2004), 893-897, DOI 10.4028/www.scientific.net/MSF.449-452.893.

2 **Kim J W, Chun H S, Ha S S, Chae J H, Joo J H, Shin Y E, Jung S B**, *Board-level reliability of Pb-free surface mounted assemblies during thermal shock testing*, Advanced Materials Research **15-17** (2007), 633-638, DOI 10.4028/www.scientific.net/AMR.15-17.633.

3 **Gong J, Liu C, Conway P P, Silberschmidt V V**, *Analysis of Stress Distribution in SnAgCu Solder Joint*, Applied Mechanics and Materials **5-6** (2006), 359-366, DOI 10.4028/www.scientific.net/AMM.5-6.359.

4 **Hwang T K, Leeb S B**, *Effects of Microstructure on Material Behaviors of Solder Alloys*, Key Engineering Materials **297-300** (2005), 825-830, DOI 10.4028/www.scientific.net/KEM.297-300.825.

5 **Zhang X W, Lee S W R**, *Effects of Temperature Profile on the Life Prediction of PBGA Solder Joints under Thermal Cycling* **145-149** (1998), 1133-1138, DOI 10.4028/www.scientific.net/KEM.145-149.1133.

6 **Perry L. Martin**, *Electronic Failure Analysis Handbook*, McGraw-Hill, 1999.

7 **Pozsgai I**, *A pásztázó elekronmikroszkópia és az elektronsugaras mikroanalízis alapjai*, ELTE Eötvös Kiadó, 1995.

8 **Brümmer O, Heydenreich J, Krebs K H, Schneider H G**, *Szilárd testek vizsgálata elektronokkal, ionokkal és röntgensugárzással*, Műszaki Könyvkiadó, 1984.

9 **Werner J. Maiwald**, *Lötfehler*, Eugen G. Leuze Verlag, Bad Salgau, 2001.

10 **Briggs A**, *Advances in Acoustic Microscopy* **1** (1995), 1-45.

11 **Bell H**, *Reflowlöten*, Eugen G. Leuze Verlag, 2005.