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ACOUSTIC EMISSION APPLICATION FOR NONDESTRUCTIVE STRENGTH DIAGNOSTICS OF PRINTED CIRCUIT BOARDS

The paper represents developing nondestructive method for strength diagnostics of solder joints on printed circuit boards with application of acoustic emission method. Solder joints studied in the current research were performed by through-hole technology. The research methods involved static mechanical tensile and bend tests, and acoustic emission method. First solder joint strength research was conducted by static mechanical tensile tests. The batch of solder joints were tested in three equal groups: solder joints, which had no defects; solder joints, which had "cold solder" defect; solder joints, which had "low solder adhesion" defect. The load was applied with the constant speed. During the test the following acoustic emission parameters were recorded: amplitude; activity; total count in order to assess acoustic emission parameters against types of defects and find their possible correlation. Strength diagnostics conducted for solder joints performed by through-hole technology on printed circuit boards by using methods of mechanical tests with simultaneous monitoring both mechanical characteristics and acoustic emission parameters allowed to find the relationship between parameters of acoustic emission and such defects of solder joints as "cold joint" and "low solder adhesion". The pure bending technique has been developed to perform flexure tests on printed circuit boards, which provides equal testing stress condition over the printed circuit board and allows to estimate maximal acceptable load for nondestructive tests. The testing was considered to conduct in multiple load and unload cycles. The tests were conducted for the batch of double sided fiberglass foil laminated printed circuit boards, which were prepared and sorted into three equal groups by defects embedded into their solder joints. Acoustic emission data analysis indicated total count as the most informative parameter to correlate with various types of solder joint defects. Conducted experiments gave the reason to use identified character of acoustic emission to develop methods for strength diagnostics of solder joints on printed circuit boards.

Keywords: acoustic emission, strength, diagnostics, printed circuit board, solder joint

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ЗАСТОСУВАННЯ АКУСТИЧНОЇ ЕМІСІЇ ДЛЯ НЕРУЙНІВНОЇ ДІАГНОСТИКИ МІЦНОСТІ ДРУКОВАНИХ ПЛАТ

У роботі представлено розробку неруйнівного методу для діагностики міцності паяних з'єднань на друкованих платах із застосуванням методу акустичної емісії. Паяні з'єднання, досліджені в даному дослідженні, були виконані за технологією навісного монтажу. Методи дослідження включали статичні механічні випробування на розтяг та згин, а також метод акустичної емісії. Дослідження на розтяг було здійснено для партії паяних з'єднань поділеної на три рівні групи: паяні з'єднання, які не мали дефектів; паяні з'єднання, які мали дефект типу "холодна пайка"; паяні з'єднання, які мали дефект типу "неспай". Механічне навантаження подавали із постійною швидкістю. Під час випробування було зареєстровано наступні параметри акустичної емісії: амплітуда; активність; загальний рахунок, з метою порівняння параметрів акустичної емісії з типами дефектів і знаходження їх можливої кореляції. Проведена діагностика міцності за допомогою методів механічного навантаження з одночасною реєстрацією як механічних характеристик, так і параметрів акустичної емісії, дозволила виявити зв'язок між параметрами акустичної емісії та дефектами пайки. Технологія чистого згину була розроблена для проведення випробувань на згин на друкованих платах, що забезпечувало рівномірне навантаження друкованої плати та дозволило оцінити максимальне допустиме навантаження для неруйнівних випробувань. Випробування проводилися в багаторазових циклах навантаження та розвантаження. Випробування проводилися для партії двосторонніх фольгованих склопластикових друкованих плат, які були підготовлені та сортовані по трьох рівних групах із заданими дефектами. Аналіз даних акустичної емісії виявив загальний рахунок як найбільш інформативний параметр для кореляції із різними типами дефектів паяних з'єднань. Проведені експерименти дають підстави використовувати ідентифікований характер акустичної емісії для розробки методів діагностики міцності паяних з'єднань друкованих плат.

Ключові слова: акустична емісія, міцність, діагностика, друкована плата, паяне з'єднання.

Introduction

Complexity and micro-miniaturization in electronic and computer production technologies constantly increase quality and reliability standards for their components. Printed circuit boards (PCB) are considered the main building blocks of modern electronics, which represent assemblies purposed to electrically connect and, what is also important, mechanically support electronic components. However operation and even technology cause mechanical interactions and forces [1], acting between PCB substrate and electronic components, and spreading through their links. Such tensile, shear, bending or torque forces cause strain and stress in substrates, which are subsequently transmitted to the bodies of components through the contact joints, which appear to be the weakest links in the assembly. The damages of the joints cause failures of the whole electronic units and therefore require detailed studying.

The general technology for components' installation onto the PCBs remains soldering although quality of soldered joints (SJ) is not always achievable due to numerous defects. Therefore one of the primary tasks to provide reliability to SJs is to apply and improve their testing methods. The range of methods for non-destructive or destructive SJ tests provided by the state standard [2, 3] does not always provide proper quality selection. SJs studied in the current research were performed by through-hole technology (THT). The research methods involved static mechanical tensile and bend tests, and acoustic emission (AE) method.

Features of acoustic emission as nondestructive evaluation method

Application of electrical and physical methods for SJ quality control attracts close attention nowadays. In accordance to [4] these methods include electro-parametric, noise, acoustic emission, exoelectronic emission, photovoltaic and recombinant radiation methods. Among these methods, the most of which have range of intrinsic disadvantages such as high cost and complexity of measuring instrumentation, method of acoustic emission recently hastened its growth due to its high applicability for nondestructive diagnostics and prediction of strength of technical objects in general and of electronic equipment in particular. Table 1 represents characteristics of AE methods in comparison with other nondestructive evaluation (NDE) methods.

Table 1

Comparative characteristics of acoustic emission methods against other NDE methods

Acoustic emission method	Other NDE methods
Detection of defects in progression	Detection of defects geometry
Load application is required for tests	Load application is not required for tests
Each test is unique	Tests are replicable
High sensitivity to material consistency	Low sensitivity to material consistency
Low sensitivity to geometry of tested object	High sensitivity to geometry of tested object
Simplicity of application	Complexity of application
Transducers require minor attachment area to fulfil monitoring of the entire tested object	Tests require reach to the full surface of tested object
The object is completely monitored by the single test	Subsequent monitoring parts of the object is required
Difficulties: sensitivity to noise	Difficulties: dependence on object geometry

Acoustic emissions [5] are pressure waves generated due to transient release of energy when a material is subjected to mechanical, in this case, thermal or chemical changes causing irreversible deformations or changes in atomic arrangement. The energy released travels as a spherical wavefront and is converted as electrical signal by transducers placed on surface of the material (fig. 1). The transducer output is filtered and amplified to eliminate ambient noise and increase the signal-to-noise ratio.

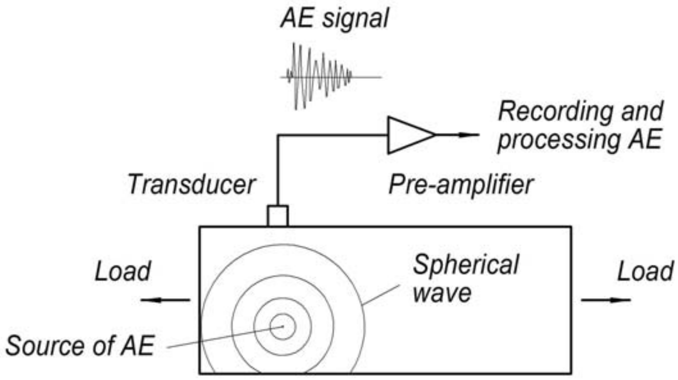

Fig. 1. The basic principle of acoustic emission generation and recording

For the analysis high frequency signal (fig. 2, a) received from the transducer is then processed to select oscillations (fig. 2, b) whose amplitudes exceed discrimination threshold of amplifier and then events (fig. 2, c). An event is considered as collection of oscillations, received within the time period of 1 ms, and then converted into one impulse of amplitude equal to maximal amplitude of oscillations collected.

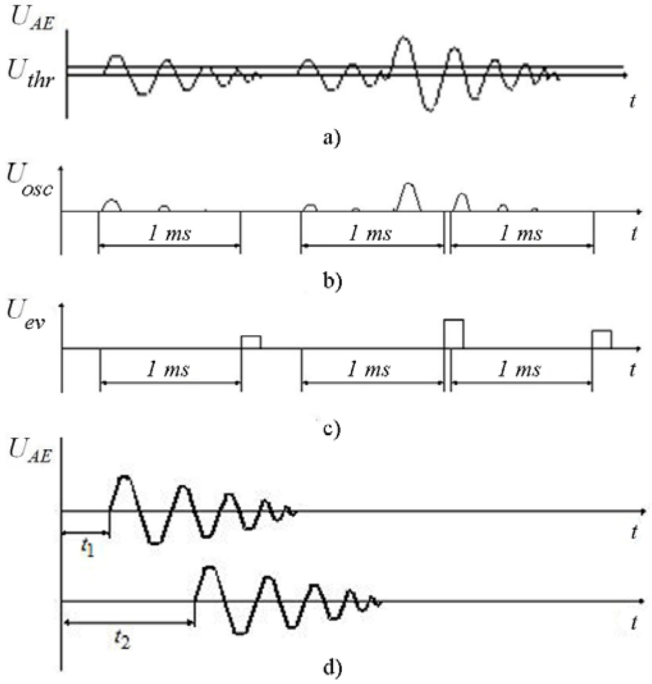

Fig. 2. Acoustic emission processing: a – acoustic emission in transducer output; b – oscillations selected; c – events converted; d – using Doppler effect for linear location

The common parameters of AE are: cumulative count of oscillations; time rate of oscillation count (count rate); cumulative count of events (total count); time rate of events count (activity); events amplitude; and linear coordinate of events, which is calculated using Doppler effect – by considering time difference of signal arrivals to two transducers $\Delta t = t_2 - t_1$ (fig. 2, d).

Acoustic emission application for solder joints tensile strength diagnostics

The soldered joint strength quality is assessed by tensile and shear ultimate strength determined by the design and technology factors.

The structure of THT solder joint consists of the metallized cylindrical hole with the electronic component lead inserted and bonded by solder alloy previously melted and filling the space around the lead and hole. The strength of such a joint is provided by the solder alloy joining lead and hole and reinforced by the through hole assembly of the joint. This joint appears to demonstrate higher resistance to shear load, due to locking effect that the hole provides to the inserted lead, unlike the tensile one.

Therefore the solder joints strength research was conducted by static mechanical tensile tests. For the experiment SJs of MLT2 resistors were taken, which were installed by THT technology on the PCB into 2 mm contact pads. The load was applied by the tensile machine IP-5057-50 with 500 N ultimate load. The load measurement tolerance was under 1 % of maximal load.

The test was performed so that one lead of the resistor was soldered to metallized hole in PCB with tin-lead alloy and fixed in the upper clamps of tensile machine. PCB was firmly fixed in custom lower clamps of the machine. The load scheme is shown in fig. 3.

Tests were conducted with an assumption that quality and hence strength of the solder joint is reduced by its defects, which are likely to appear due to variety of technological causes. In order to be able to detect defects or razor to identify reduction of SJ strength caused by defects the tests were performed for SJs with predetermined defects. For this reason the most common defects such as “cold solder” and “low solder adhesion” were embedded into the joints.

All together 60 solder joints were tested: 20 SJs had no defects; 20 SJs had “cold solder” defect; 20 SJs had “low solder adhesion” defect. The load was applied with the constant speed of 0.1 mm per minute. During the test the following AE parameters were recorded: amplitude; activity; total count in order to assess acoustic emission parameters against types of defects and find their possible correlation.

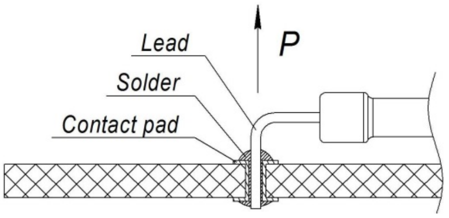

Fig. 3. Solder joint tensile test load scheme

The experiments indicated the lowest tensile strength for SJs having “low solder adhesion” defect. The ultimate load sustained by SJs with such defects was 30-40 N. In the end, the leads were pulled out of the solder with no acoustic emission detected.

Since the case when leads are not wetted completely is very unlikely, studying SJs with partly wetted leads would be more reasonable. Therefore, in further experiments, the defects of low solder adhesion are considered those produced by insufficient (partial) wetting SJ parts. The average load sustained by such SJs made 70-80 N. For comparison, the average breaking load for SJs with cold joint defect made 44 N, and 116 N – for no defect SJs.

As foreseen, the AE character differed for different defects. AE data analysis resulted in total count N (impulses, imp) and maximal activity A_{max} (impulses per second, imps) parameters measured for different types of SJs during their tensile tests. For cold joint defects N = 70 imp and A_{max} = 210 imps; for low solder adhesion N = 22 imp and A_{max} = 40 imps; for no defect SJs N = 34 imp and A_{max} = 51 imps. Fig. 4 demonstrates acoustic emission diagrams produced by the load progression applied during tensile tests for three groups of SJs with mentioned types of defects. The diagrams show AE in the load range from 0 to 44 N what corresponds to average ultimate load for the cold joints and makes 40 % of ultimate load for no defect joints.

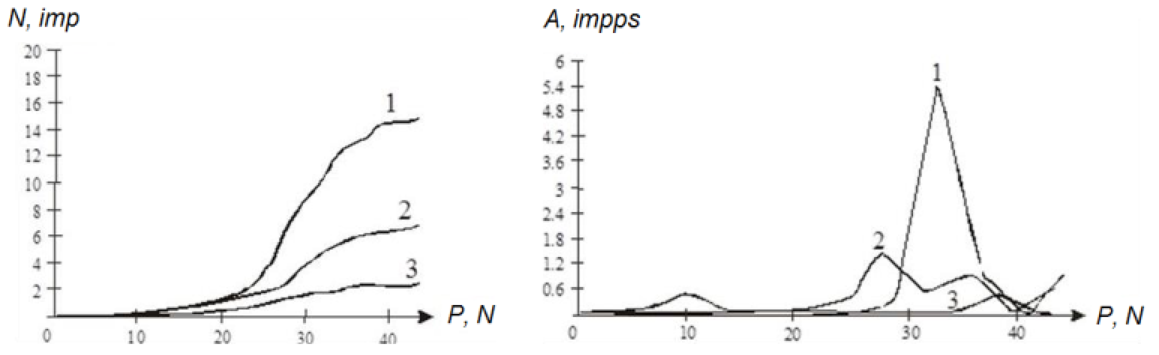

Fig. 4. Acoustic emission – load diagrams during tensile tests of three types of solder joints:
1 – cold joints; 2 – low solder adhesion joints; 3 – solder joints without defects

Statistical analysis of experimental data testified of decreasing ultimate load levels for defective SJs with 95 % confidence probability: cold joint defect lowers SJ strength by 62 % in average; low solder adhesion defect lowers SJ strength by 35 % in average. At the same time analysis of acoustic emission detected along the tests shows sensitivity and applicability of this method to detect defects in SJs and even assess their strength. Besides, it holds potential for nondestructive diagnostics of solder joints long before the final destruction.

Pure bending technique for printed circuit boards flexure test

Conducting tensile tests with simultaneous recording acoustic emission showed perspectives for nondestructive strength diagnostics of electronic components solder joints installed on PCB, although practical application of the method was limited by monitoring only the single component joints at the time. In order to overcome this limitation and conduct tests for entire PCB with all electronic components installed the pure bending technique was applied (fig. 5) [6]. The pure bending was designed to provide equal testing stress over the PCB area as applied in between two supports. Thus all SJs installed within the tested area can be monitored simultaneously.

PCBs populated with electronic components were now the research objectives. SJ strength assessment considers solder mechanical characteristics, which are specified with consideration of design and technology of the joint. The strength of low-melting solders in cast phase is less than that of SJ. The lowest level of ultimate strength for solder POS40 in the cast phase is $\sigma_u = 40$ MPa [7].

The ultimate strength for fiberglass substrate is $\sigma_u = 45$–100 MPa.

Assuming ultimate strength of the solder as the reference value the test stress is calculated by the formula:

$$\left[\sigma\right] = \frac{\sigma_u}{n} = \frac{40}{2.5} = 16\,MPa, \tag{1}$$

where σ_u – ultimate strength, $n = 2.5$ – safety factor.

The possible inaccuracy entailed by no account for design and technology of the joint will deposit into the safety factor. Obtained safety factor is sufficient to provide safe testing stress σ_{test} within proportionality strain area of solder material, so that solder is subjected to only elastic deformations, which do not reduce its strength.

Then the load P applied to PCB is specified for the nondestructive tests. Load application scheme for PCB test is shown in fig. 5.

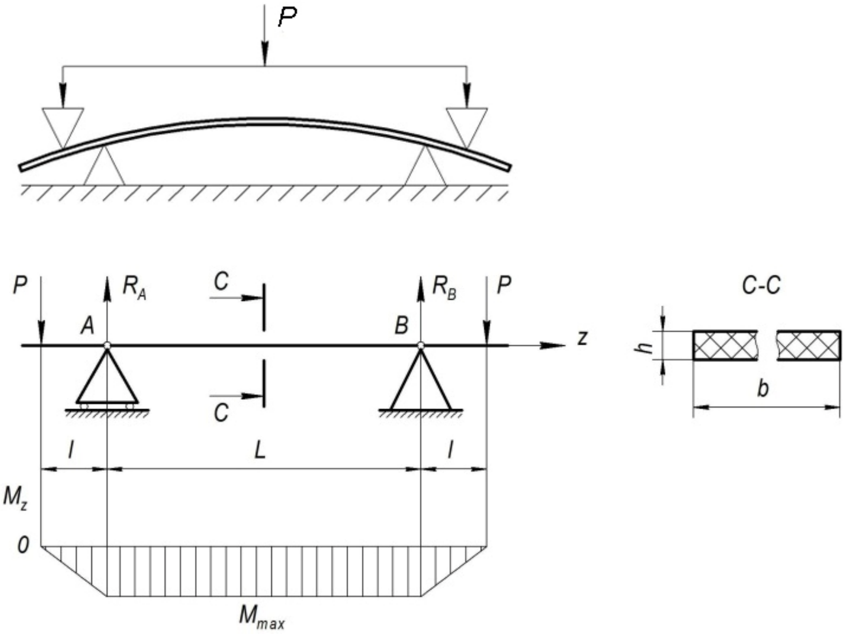

Fig. 5. Pure bending load application and diagram of internal bending moments in PCB

Maximal stress [7] is produced in dangerous part of PCB cross section – in peripheral layer, where bending moments are maximal $M = M_{max}$. In pure bending area with length L which is created by and lays in between two supports A and B, maximal stress is found by formula:

$$\sigma_{\max} = \frac{M_{\max}}{I_{ax}} y_{\max}, \tag{2}$$

where M_{max} – maximal bending moment produced by load P; I_{ax} – axial moment of inertia; y_{max} – maximal distance from the neutral line of the cross-section to the peripheral layer (fibers); $y_{max} = h/2$, where h – thickness of PCB substrate.

Since ratio I_{ax}/y_{max} represents axial moment of resistance W_{ax}, formula (2) will be shortened to:

$$\sigma_{\max} = \frac{M_{\max}}{W_{ax}}. \tag{3}$$

As required by strength condition of normal stress under bending load – maximal stress produced by the applied load should comply with acceptable standard $[\sigma]$:

$$\sigma_{max} \le [\sigma]. \tag{4}$$

Performing nondestructive tests to PCBs requires maximal acceptable load estimation.

Using formulas (3) and (4) for which in accordance to load application scheme (fig. 6) maximal bending moment equals:

$$M_{max} = P \cdot l, \tag{5}$$

and axial moment of resistance of rectangular section [6] is expressed as:

$$W_{ax} = \frac{b \cdot h^2}{6}, \tag{6}$$

maximal acceptable load for nondestructive bending tests of PCBs should comply with condition:

$$[P] = \frac{b \cdot h^2}{6 \cdot i}[\sigma]. \tag{7}$$

Pure bending flexure strength tests of printed circuit boards solder joints

Pure bending tests conducted by tensile machine IP-5057-50 indicated that the activity of acoustic emission responds to the speed, at which load is applied. Since AE data analysis requires its essential amount the decision was made to conduct tests at maximal acceptable loading speed of 100 millimetres per minute. The load was applied under acceptable limit calculated by the formula (3) $P_{test} = 36$ N.

However single load had not produced a considerable activity of AE signals yet and the testing was considered to conduct in multiple load and unload cycles. Each PCB was tested in 5 cycles. Minimal and maximal stresses in cycles were $\sigma_{\min} = 0$ MPa and $\sigma_{\max} = 16$ MPa correspondently. Acoustic emission was recorded during all the tests by piezoelectric gauges and via pre-amplifiers at frequency band of 0.02-0.2 MHz. The gauges were attached to PCB surface through the layer of acoustic paste.

The tests were conducted for 60 double sided fiberglass foil laminated PCBs (320×120×1.5×0.1 mm size). For the experiment PCBs were prepared and sorted into three equal groups by defects embedded into their solder joints: 1) PCBs with no defects; 2) PCBs with cold joint defects; 3) PCBs with low solder adhesion defects. Each PCB was populated with one component – resistor MLT-2. In group 1 resistors were installed in compliance with technological standard [8, 9]. In group 2 one of the resistors' leads was mounted to PCB as a cold joint, in particular as "circle crack" joint which is likely for soldering technology. In the group 3 low solder adhesion defects were embedded into solder joints for what resistors' leads had not been wetted before soldering.

During the tests the following AE parameters [5] were recorded: amplitude; activity; total count. The test results indicated that PCBs with no defect solder joints do not radiate acoustic emission during all cycles. The total count of SJs with low solder adhesion defects made 10-15 imp with amplitude 1 mV. Normally such signals are radiated at load progression and in the moments of maximal load. Signals radiated by cold joint defects are characterized by considerably higher total count (30-40 imp) with amplitude up to 3 mV. The specificity of cold joints is that AE appears on load discharging phase of cycles, what can be explained by cracks converging their edges. Figures 7, 8 demonstrate acoustic emission – cycling load diagrams recorded during pure bending tests of PCBs with embedded solder joint defects.

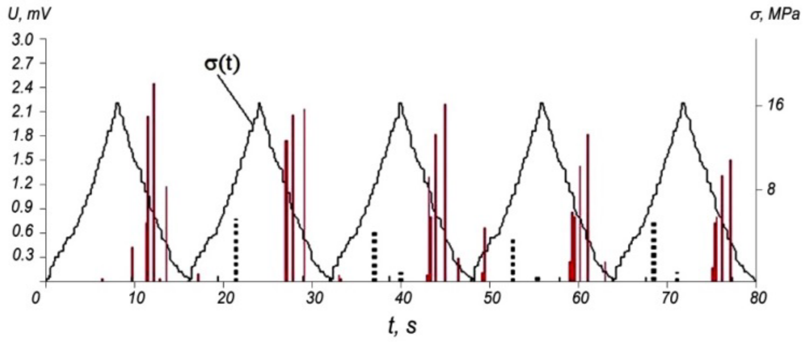

Fig. 6. Acoustic emission amplitude – cycling load diagram: solid line – low solder adhesion; dash line – cold joint

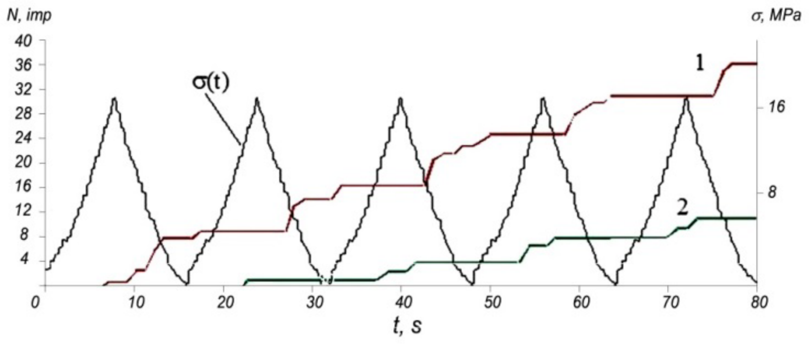

Fig. 7. Acoustic emission total count – cycling load diagram: 1 – cold joint; 2 – low solder adhesion

AE data analysis indicated total count as the most informative parameter to correlate with various types of solder joint defects. Conducted experiments give the reason to use identified character of acoustic emission to develop methods for strength diagnostics of solder joints on printed circuit boards [10].

Nondestructive method for solder joint strength diagnostics with acoustic emission application

1. Printed circuit boards are tested by pure bending load under acceptable limit specified by the safety factor for solder material n = 2.5.

2. In case acoustic emission is detected, test is repeated in 5 load/unload cycles. Acoustic emission progression during cycle test indicates of solder joint defect and such PCB is rejected and classified as joint with growing defect.

3. When required defect location is performed in order to repair it.

The developed method has been tested out on the batch of industrial printed circuit boards. The tests were conducted for 32 single sided fiberglass foil laminated PCBs (120×140 mm size).

During tests acoustic emission was detected for three PCBs what indicated progressing defects.

Analysis of AE character identified type of the detected defects – low solder adhesion, which was then proved by detailed optical 10x zoom revision of rejected PCBs in places where AE was located. Defects were also tested by passing electric current through the defected solder joints and measuring their electric resistance. Since PCBs had been used for a long time before the tests and identified defects had remained hidden so they can have developed during their further operation and would have caused a failure of the whole electronic unit.

Conclusion

Strength diagnostics conducted for solder joints performed by through-hole technology on printed circuit boards by using methods of mechanical tensile and pure bending tests with simultaneous monitoring both mechanical characteristics and acoustic emission parameters allowed to find the relationship between parameters of acoustic emission and such defects of solder joints as “cold joint” and “low solder adhesion”.

The pure bending technique has been developed to perform flexure tests on printed circuit boards, which provides equal testing stress condition over the printed circuit board and allows to estimate maximal acceptable load for nondestructive tests.

Nondestructive method for strength diagnostics of solder joints on printed circuit boards that uses pure bending cycling tests with application of acoustic emission method has been designed.

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